Union of Concerned Scientists
ucsusa.org Two Brattle Square, Cambridge, MA 02138-3780 t 617.547.5552 f 617.864.9405
1825 K Street NW, Suite 800, Washington, DC 20006-1232 t 202.223.6133 f 202.223.6162
500 12th Street, Suite 340, Oakland, CA 94607-4087 t 510.843.1872 f 510.843.3785
One North LaSalle Street, Suite 1904, Chicago, IL 60602-4064 t 312.578.1750 f 312.578.1751

February 20, 2020

Administrator Andrew Wheeler
U.S. Environmental Protection Agency
EPA Docket Center, Air and Radiation Docket
Mail Code 28221T
1200 Pennsylvania Avenue NW
Washington, DC 20460

RE: Advanced notice of proposed rulemaking—Control of air pollution from new motor vehicles: Heavy-duty engine standards (Cleaner Trucks Initiative), Docket No. EPA-HQ-OAR-2019-0055

Dear Administrator Wheeler,

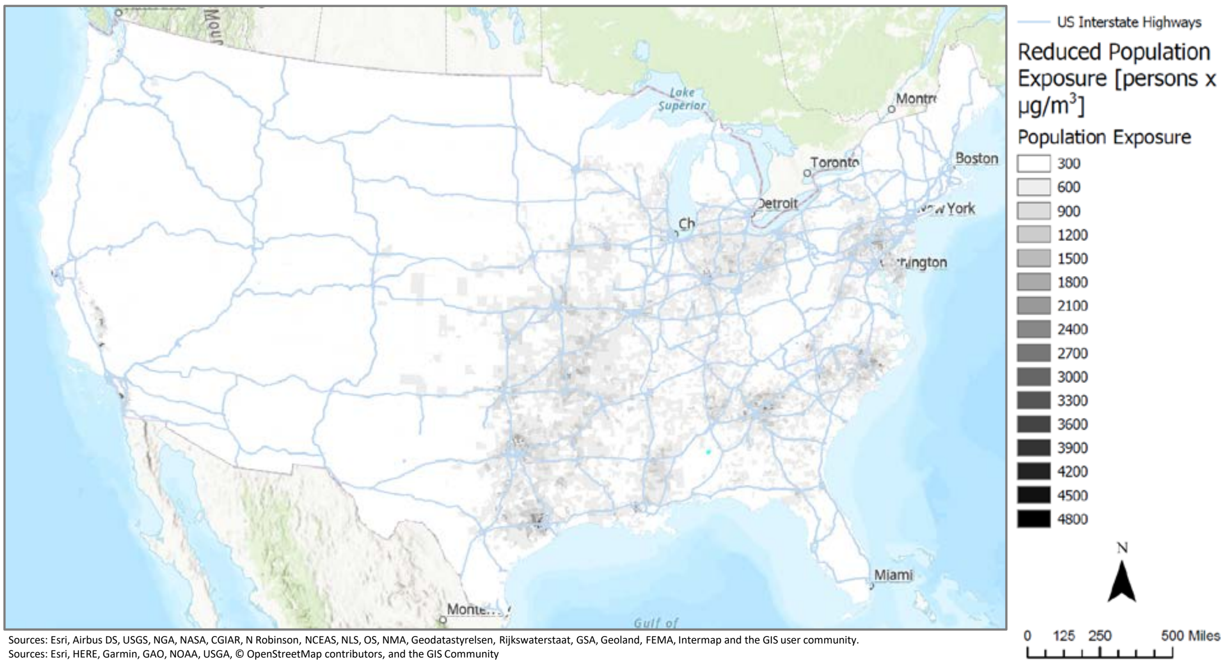
On behalf of our half million members and supporters, the Union of Concerned Scientists (UCS) submits the below comments on the control of air pollution from new heavy-duty vehicles, referred to by the administration as the Cleaner Trucks Initiative (CTI). Summarized below, our full technical comments on Environmental Protection Agency's (EPA's) advanced notice of proposed rulemaking (ANPRM) can be found in the attached technical appendix. Our comments respond both to specific questions raised by the agency and the need for the agency to regulate the harmful smog-forming pollution and soot from heavy-duty vehicles, paying particular attention to state leadership on this issue and the forthcoming regulation from the California Air Resources Board (CARB).

As EPA has well established, nitrogen oxides (NO_x) and particulate matter (PM) emitted from heavy-duty trucks are a significant contributor to poor air quality that contributes to adverse health impacts, including but not limited to, increased hospitalizations related to asthma, particularly in children (EPA 2016); increased cardiovascular disease, including heart attacks (EPA 2019a); and increased risk for respiratory illnesses and infections (EPA 2019b).

Importantly, these health impacts are not borne uniformly across the population—due to the systemic and structural racism of the United States, communities of color are more likely to live near highly polluted areas, including near highly trafficked roadways and interstates utilized by the heavy-duty trucks as well as ports and freightyards with a high concentration of truck traffic (Pratt et al. 2015). For this reason, our analysis shows that the communities currently most exposed to this harmful truck traffic are poised to benefit disproportionately from regulations controlling NO_x and PM.

CARB is moving forward to address this issue, having proposed strong regulations that help move California closer to its air quality targets (CARB 2019a); and a number of "Section 177" states have highlighted how a strong rule could help them achieve their own air quality goals (Clyne 2019,

FIGURE ES-1. Map of particulate emissions reductions resulting from an ultralow NO_x rule



Because heavy-duty emissions track strongly with freight corridors, the benefits of a strong rule to limit nitrogen oxides and particulate matter emissions are concentrated along highly trafficked areas like interstates and ports. Of particular note is the widespread nature of the rule's benefits.

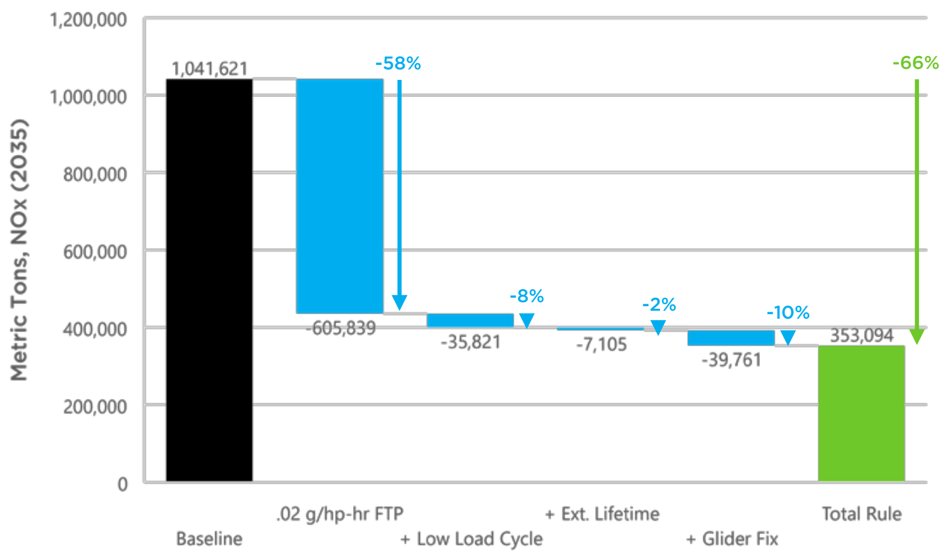
SOURCE: PRELIMINARY UCS ANALYSIS.

Cooper 2019, Decker 2019, Farrell 2019, Feeley 2019). However, the entire country stands to benefit from a regulation in line with CARB's own proposed regulations (Flint and White 2019) (Figure ES-1).

A 90 percent reduction in NO_x emissions on the heavy-duty federal test procedure (FTP) would yield substantial benefits, but there are complementary opportunities as well that EPA should consider as it moves forward with its own regulation, including the adoption of a low-load cycle (LLC), extending the lifetime and warranty requirements, and adopting a more stringent PM standard to reduce any chances of backsliding (Figure ES-2). Further steps EPA should adopt as part of this regulation to ensure the progress necessary nationwide to address NO_x and PM include the incorporation of a low-emissions idling target and a requirement that beginning in 2027 glider trucks must include MY2010-compliant engines or better. Each piece of this regulatory framework builds upon work by CARB in the precise way envisioned by the authors of the Clean Air Act, benefiting from California as a "testing area" for more stringent pollution standards.[1]

[1] "To date only California has actively engaged in this form of pollution control [from mobile sources] and, in fact, the initial Federal standard is based on California's experience. … The Nation will have the benefit of California's experience with lower standards which will require new control systems and design. In fact California will continue to be the testing area for such lower standards and should those efforts to achieve lower emission levels be successful it is expected that

FIGURE ES-2. Emissions of nitrogen oxides from heavy-duty trucks in 2035



While emissions of nitrogen oxides from trucks in 2035 are expected to be just less than half those of today, thanks to the phase-in of current regulations, adopting a rule comparable to CARB's proposal would cut those remaining emissions by about two-thirds.

Note: Percentages are multiplicative, not additive, and refer to the additional emissions reductions from previous stage.
SOURCE: UCS ANALYSIS.

Any rule aiming to reduce NO_x and PM must also consider the rapid development of "zero emission" technology. A number of medium- and heavy-duty applications have already shown that electric vehicles are competitive with fossil fuel-powered vehicles in terms of a total cost of ownership (TCO). Additionally, state and federal incentives as well as novel regulations like CARB's forthcoming Advanced Clean Trucks rule will further accelerate the development of these technologies. While the CTI program may not be the only avenue to further the rapid adoption of this technology, EPA's rule must recognize that ongoing transition and accelerate such continued innovation as is possible.

It is critical as EPA moves forward with its regulations that it base its conclusions on the best available data. EPA's proposal to move forward with its regulations without first finalizing its ongoing research on the cost and capability of the technologies which can be deployed to cut pollution from heavy-duty trucks is unnecessary and ill advised (see, e.g., 85 FR 3307 and 85 FR 3329). EPA has a four-year lead-time requirement for its rulemaking, and it has committed to aligning its regulations with the 2027 schedule of the greenhouse gas rule—as such, there is no legitimate need to rush this rulemaking. Furthermore, the as-of-yet incomplete data is of the utmost importance and foundational to any rulemaking—incorporating it post-NPRM would likely require an additional notice and a public

the Secretary will, if required to assure protection of the national health and welfare, give serious consideration to strengthening the Federal standards." – Record of the 113th Congress, Senate, July 18, 1967, p. 19182, regarding the Air Quality Act of 1967, which amended the Clean Air Act of 1963 to include an exemption for California.

comment period. The most appropriate action would be for EPA to finalize the data, put it in the public sphere, and then issue the NPRM.

It has been nearly 20 years since EPA last addressed this issue, and while the standards have largely been working, there is still considerable room for improvement. With a transition to zero-emission vehicles already underway, and the lengthy timeframe of the CTI program, it is possible that this could be the last set of pollution standards set for fossil fuel-powered trucks. Given the scope of the problem and the longevity of such a rule, EPA should make sure that a future notice of proposed rulemaking (NPRM) reflects the long-term opportunities to reduce emissions from the truck fleet and the best available data on technologies available in the coming decade. Such a "technology-forcing" rule is required under the Clean Air Act and will ensure that those emissions are reduced as much as possible and with those reductions guaranteed for as long as the vehicle remains on the road. Accomplishing this will take careful analysis building upon the large body of evidence collected already by CARB and currently underway by the Agency itself.

Strong NO_x and PM standards for heavy-duty trucks can help clear the air for millions of Americans dealing with the public health costs of our fossil fuel-powered economy (Figure ES-1). Any EPA proposal should carefully consider the full breadth of scientific and technical evidence to maximize medium-term emissions reductions while supporting a transition to a zero-emission transportation sector as quickly as possible. The health of our nation's most vulnerable depends on it.

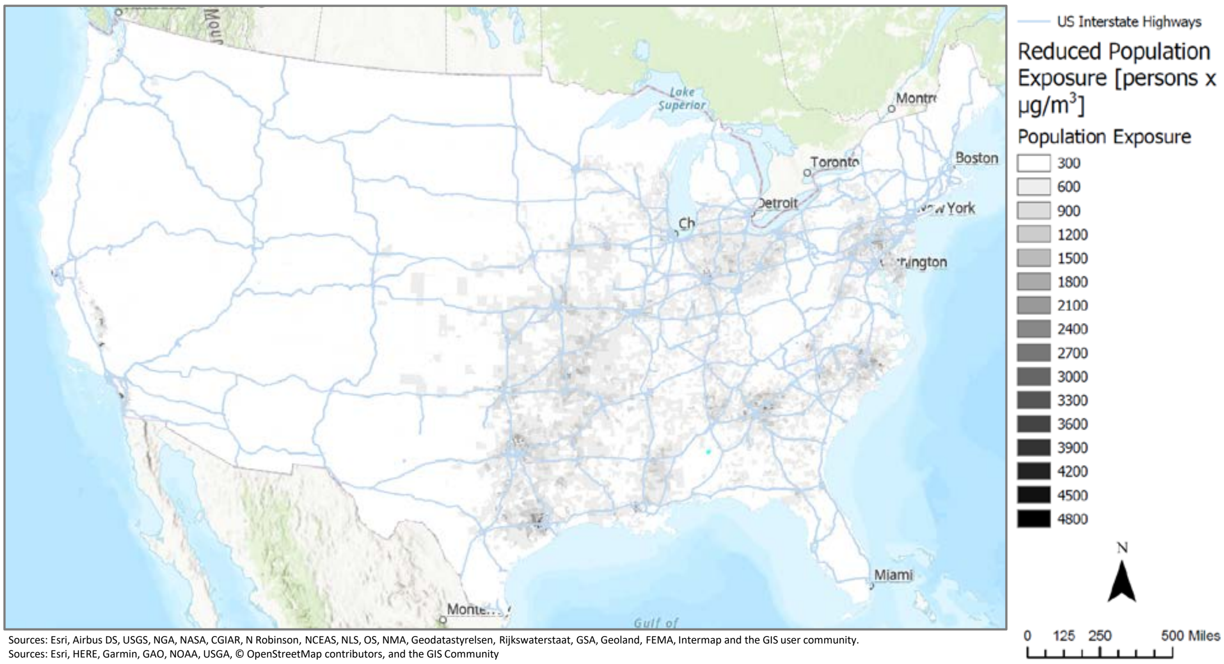
Sincerely,

Dr. Dave Cooke
Senior Vehicles Analyst

Comments Concerning the Advanced Notice of Proposed Rulemaking to Control Air Pollution from New Heavy-duty Trucks (i.e., Cleaner Trucks Initiative): Technical Appendix

Referencing docket ID number:
EPA-HQ-OAR-2019-0055

FIGURE 1. Map of particulate emissions reductions resulting from an ultralow NO_x rule



Because heavy-duty emissions track strongly with freight corridors, the benefits of a strong rule to limit nitrogen oxides and particulate matter emissions are concentrated along highly trafficked areas like interstates and ports. Of particular note is the widespread nature of the rule's benefits.

Note: This data is preliminary and underestimates benefits to California due to differences between MOVES and EMFAC. Because EPA denied our request for an extension of the comment period, this error was not corrected before the public comment deadline.

SOURCE: PRELIMINARY UCS ANALYSIS.

I. Rationale for rulemaking

In general, we concur with EPA's assessment that "heavy-duty vehicles will continue to be one of the largest contributors to the mobile source NO_x inventory" (85 FR 3306) and, as such, warrants additional regulation. Detailed below are some of the critical air quality and health implications of reducing NO_x and $PM_{2.5}$.

A. Air quality targets

As acknowledged by EPA, heavy-duty truck pollution is a critical factor that will need to be addressed in order for many regions of the country to achieve their air quality targets (e.g., SCAQMD et al. 2016 [Figures 6-8] and Cooper 2019). This need for action is made even more important given EPA's numerous rollbacks of emissions regulations over the past few years, all of which would have otherwise reduced the very emissions the CTI is meant to address, including replacing the Clean Power Plan with the Affordable Clean Energy rule, revising the Mercury and Air Toxics standards, and rolling back greenhouse gas emissions and fuel economy standards for light-duty vehicles (Reed et al. 2020).

FIGURE 2. Air quality benefits of ultralow NO_x standards in 2035, by census tract and race

Due to an history of inequity when it comes to air pollution exposure, air quality benefits are not distributed equally by race around the country. In general, African Americans see a broadly disproportionate local air quality benefit from these rules, with the population of African Americans concentrated in more highly trafficked areas where they are exposed to diesel-related emissions (the overall proportion of benefits to African Americans exceed their share of the population and are skewed to the right side of the figure where local benefits are greater). The story for Americans identifying as Hispanic/Latinx is not as clear-cut, though the benefits are: many Hispanics/Latinxs in the United States live in more dispersed regions of the Southwest, where overall truck emissions are below the national average, and thus do not broadly experience a significantly different air quality benefit than white Americans; however, the areas of the country which will experience the greatest benefits from an ultralow NO_x rule (shown on the right side of the figure) are some of the areas of the country with the greatest concentration of those identifying as Hispanic/Latinx (and the least share of white Americans).

Note: Racial/ethnicity data is based on self-identification for the U.S. Census. Equal areas in the graph represent the same level of reduced population exposure. The degree to which the benefits are distributed non-uniformly can be characterized by the degree to which the colored bars fall outside the average population share—e.g., the large bar of red at the right of the graph indicates that the greatest local air quality benefits are in areas with a larger share of the population identifying as Hispanic/Latinx than the national average.
SOURCE: PRELIMINARY UCS ANALYSIS.

B. Health impacts

NO_x is a precursor to ozone as well as nitrate particulates. Exposure to ozone can result in decreased lung function and aggravate asthma, and there is evidence suggestive of cardiopulmonary-related mortality resulting from short-term exposure to ozone (EPA 2019b). Long-term exposure not only likely causes respiratory illness but also metabolic effects including inflammation, decreased liver function, and even mortality related to diabetes or other cardiometabolic diseases.

Exposure to particulate matter (in particular, $PM_{2.5}$) causes cardiovascular impacts including increased blood pressure, impaired heart function, and cardiac arrest (EPA 2019a). Recent evidence supports a likely causal relationship between long-term exposure to $PM_{2.5}$ and cancer, particularly lung cancer, with evidence supporting reduced cancer survival rates as well.

There is a growing body of evidence that ultrafine particles with diameters well below 2.5 microns have unique health implications (Ohlwein et al. 2019). Currently, the evidence suggests that short-term exposure to ultrafine particles could yield unique inflammatory and cardiovascular health impacts separate from the effects of other pollutants. There is also a growing body of evidence from animal toxicological studies that is suggestive of nervous system effects (EPA 2019a).

A strong rule which reduces NO_x and $PM_{2.5}$ thus has the potential for significant health-related impacts, including not just reduced mortality but reductions in hospitalizations for respiratory and cardiovascular illnesses and reductions in lost workdays. These impacts are clearly most significant to the individuals and families experiencing these health impacts but also have broader ramifications and economic costs to their local communities and to the country as a whole.

C. Inequity of air pollution

In addition to the immediate health benefits provided broadly by stronger NO_x and PM standards for heavy-duty trucks, it is important to recognize the local benefits to communities suffering most from local, freight-related pollution. Communities of color are disproportionately exposed to pollution from heavy-duty trucks (Pratt et al. 2015), resulting from a history of racial injustice owing to issues like the lack of political power on issues of siting for major sources of pollution like ports and freeways and discriminatory housing practices (Mohai et al. 2009).

Because communities of color are disproportionately exposed to the harmful emissions of trucks at the local level, these communities stand to disproportionately benefit from efforts to reduce those emissions. In that sense, a strong CTI program can help promote environmental justice and reduce the inequity of transportation emissions.

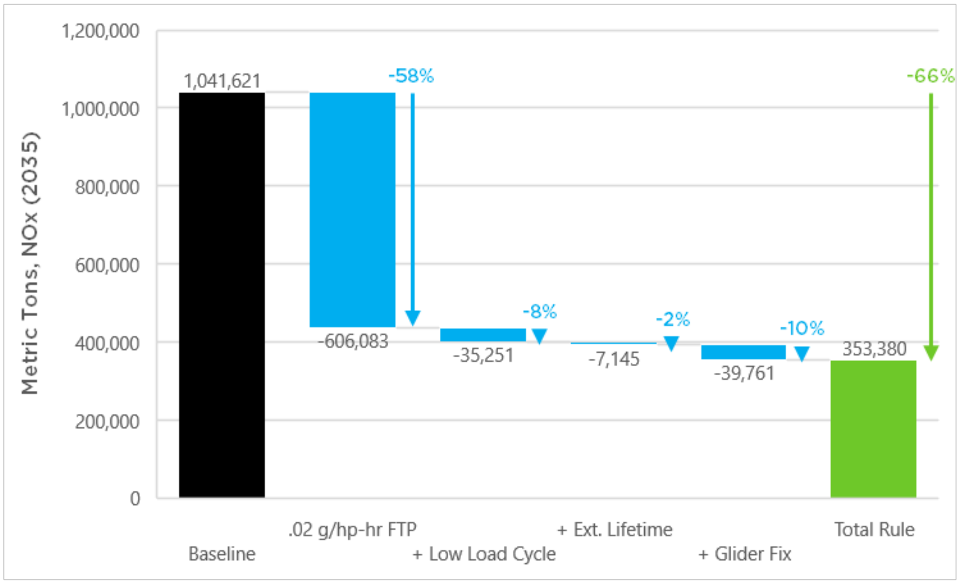
We have modeled the impacts of a strong rule based on the a nationalized adoption of the proposal presented by CARB in 2019 (CARB 2019a, 2019b, 2019c), along with a requirement that glider vehicles use model year 2010 engines or better beginning in 2027 (see Section II and Appendix A for more detail). Using the InMAP modeling tool (Tessum et al. 2017), we have assessed the total reduction in $PM_{2.5}$ as a result of NO_x emissions reductions, while maintaining a strong PM standard.

The difference in exposure in 2035 with and without this rule shows how the benefits are distributed nationwide but are focused on specific communities near cities, freeways, and ports (Figure 1). Importantly, it is not just individual states like California with some of the most highly concentrated areas of pollution that would benefit from a strong rule, but entire regions including the Southeast, Midwest, and Northeast, all of which experience heavy truck traffic.

It is possible to assess the disproportionate benefit to communities of color as a result of this policy by combining census data with the exposure data (Figure 2). This shows quite clearly that while a strong policy to cut truck emissions would diminish the country's risk overall, African Americans experience a significantly greater local air quality improvement than average. Hispanic/Latinx communities overall are not disproportionately affected compared to the national average due to a substantial share of those identifying as Hispanic/Latinx living in less dense areas of the Southwest with relatively low exposure to truck emissions, but the communities which experience the greatest local reductions in exposure are disproportionately Hispanic/Latinx.

While heavy-duty truck emissions are only one part of the gross environmental inequity experienced by communities of color, this analysis provides some evidence that with a strong CTI

FIGURE 3. Emissions of nitrogen oxides from heavy-duty trucks in 2035



While emissions of nitrogen oxides from trucks in 2035 are expected to be just less than half those of today, thanks to the phase-in of current regulations, adopting a rule comparable to CARB's proposal would cut those remaining emissions by about two-thirds.

Note: Percentages are multiplicative, not additive, and refer to the additional emissions reductions from previous stage.
SOURCE: UCS ANALYSIS.

program, EPA will be making progress toward addressing this injustice. EPA should therefore ensure that its rulemaking adhere to the current guidance for EPA under Executive Order 12898 and consider equity and environmental justice when considering all aspects of the rulemaking process, including citing of the required public hearings other aspects of the public participation process as well as appropriate quantification of the environmental justice impacts of the rule.

II. Regulatory design

While we are not requesting comment on whether CARB should adopt these updates, we are requesting comment on the extent to which EPA should adopt similar provisions, and whether similar EPA requirements should reflect different stringency or timing. (85 FR 3311)

CARB has had a multi-year head start on the development of its program, holding multiple workshops and adjusting its proposals in response to stakeholder feedback, including that of the regulated industry. With its regulation expected to be finalized ahead of EPA's CTI, EPA is in a position to learn from and build upon this strong state leadership, as intended by Section 209 of the Clean Air Act.

California's program would lead to a tremendous reduction in NO_x emissions in 2035 if adopted nationally, and because that is explicitly the role that California was meant to play under the Clean Air Act, EPA should move forward with a program that builds upon this strong foundation. Adoption of CARB's provisions, along with added elements addressing deficiencies in federal regulation of heavy-duty vehicles, could reduce 2035 NO_x emissions by 66 percent (Figure 3). Details of the program are described below.[2]

A. FTP test cycle improvement

Based on available information, it is clear that application of the diesel technologies discussed in Sections III.A.1 should enable emission reductions of at least 50 percent compared to current standards over the FTP and RMC cycles.[87 88] Some estimates suggest that emission reductions of 90 percent may be achievable across the heavy-duty engine market by model year 2027. We request information that would help us determine the appropriate levels of any new emission standards for the FTP and RMC cycles. (85 FR 3320)

NO_x emissions from heavy-duty vehicles have been halved over the past decade (Han et al. 2019), thanks in large part to a phase-in of the standards which cut emissions on the FTP by 95 percent in just over a decade (1998-2010). Direct tailpipe emissions of PM have seen an even greater drop in emissions, thanks to diesel particulate filters (DPFs) which resulted in significant overcompliance with the 2007 $PM_{2.5}$ standard (EPA 2019c).

Moving forward, the FTP test cycle can continue to play a critical role in driving emissions reductions, even if it should be supplemented by additional procedures that better capture real-world behavior (e.g., see Section II.B). While the FTP cycle overweights operation with a hot catalyst relative to real-world behavior (Boriboonsomsin et al. 2018, Zhang et al. 2019), it still captures a wide range of speed and load characteristics. Achieving a 90 percent reduction on the FTP cycle in 2027 will thus require significant reduction of cold-start emissions as well, even if it may be leaving opportunities for further emissions reductions on the table.[3]

Our model estimates that achieving a 90 percent reduction on the FTP cycle, even without fully addressing low-load emissions, would achieve a 58 percent reduction in NOx emissions in 2035 compared to the status quo (Figure 3), a reduction of more than 80 percent from 2014 levels in spite of increases in vehicle miles traveled (VMT).[4]

B. Low-load cycle

EPA requests comment on the addition of a low-load cycle, the appropriateness of CARB's Candidate #7 low-load cycle, or other engine operation a low-load cycle should encompass, if adopted. (85 FR 3321)

According to EPA's in-use data, emissions under low speed operations (< 25 mph) are 7 times higher than those at high speed (> 50 mph) and represent a disproportionate share of NO_x emissions compared to fuel use (Badshah et al. 2019). This is in large part due to two, related factors: 1) trucks spend a much higher share of idling in the real world than is captured in the current tests, and 2) the long idle times and pattern of low-load use means that low-load operations spend a disproportionately large share of time at sub-optimal catalyst temperatures.

---

[2] Some features of the program like expanded in-use testing and a "backstop" PM standard were not modeled explicitly.

[3] Our model estimates that there is approximately a 6X difference in hot-start and cold-start emissions on the FTP cycle. In 2027, this disparity grows to more than 8X but is limited by the 14 percent weighting of the cold-start test.

[4] Our model assumes an interim standard of 0.05 g/bhp-hr in 2024 as well, consistent with CARB's rule and acting as a way to "phase in" the 2027 standard. Without any improvement in standards from today through 2026, the total NO_x reductions in 2035 would be only 48 percent.

TABLE 1. Relative emissions on the FTP and proposed LLC test cycles, for a nominal engine

	2024 FTP improvement	2024 Real-world improvement	2024 LLC/FTP ratio	2027 FTP improvement	2027 Real-world improvement	2027 LLC/FTP ratio
w/o LLC	-75%	-75%	9X	-90%	-90%	6X
w/LLC	-75%	-80%	4X	-90%	-93%	2X

Improving emissions on a low-load cycle better captures real-world emissions reductions not represented on the FTP cycle. While reducing emissions on the FTP cycle does require reductions in cold- and hot-start conditions, the relative ratio of cold and warm (as compared to hot) catalyst operation in the real world mean instituting additional requirements on low-load operation will yield real-world emissions reductions that go beyond that found on the FTP test procedure.

Note: Percentages are relative to 2010 standards (0.2 g/bhp-hr, on the FTP test) and reflect CARB's latest proposal for 2024 and 2027 (CARB 2019a). Real-world improvement reflects UCS estimate of g/mi for long-haul combination tractor-trailers.
SOURCE: UCS ANALYSIS.

While there is some significant range of operating conditions (Boriboonsomsin et al. 2018), even data on line-haul trucks show significant time spent with the catalyst well below light-off temperatures. Analysis of these impacts show that moving forward, low-load emissions are anticipated to become a greater and greater share of the overall emissions from heavy-duty trucks (Yoon et al. 2017), signifying a need for heavy-duty test procedures to better capture real-world operation.

As noted by EPA (85 FR 3321), CARB is planning to adopt a low-load test cycle, designed explicitly to reflect the datasets excluded from the FTP and RMC-SET tests (CARB 2019d). The test includes both transitioning between high- and low-load as well as sustained low-load operations, and both long and short idling periods. While running a contemporary engine through a selection of low-load test cycles, neither the primary candidate (#7) nor two alternates (#8 and #10) saw the catalyst temperature exceed 250°F over the more-than-hour-long cycle (CARB 2019d), evidence that the low-load cycle (LLC) can be used to directly measure the engine conditions current yielding a disproportionate share of emissions.

Using simulated data on catalyst temperature on the FTP (Salehi and Stefanopoulou 2018), data on catalyst efficiency versus temperature (Boriboonsomsin et al. 2018) and EPA heavy-duty in-use data (Sandhu and Sontag 2016), we've estimated cold- and hot-start performance on the FTP cycle for the different operating modes in EPA's MOVES model. We have then used the cold-start emissions to estimate behavior under CARB's proposed LLC (#7). For a baseline 2010-compliant engine, we find a difference between the LLC and FTP cycle of nearly a factor of 8—this is roughly consistent with Southwest Research Institute data on the new LLC cycle (Sharp 2019).[5]

In order to estimate how well the gap between hot- and cold-start tests could be closed, we assumed proportionally quicker warm-up times compared to today's engines, along with proportionally slower cooling times—this is nominally similar behavior to passive thermal management strategies noted by EPA (85 FR 3313). To compare the effects of an LLC cycle, we compare engines which nominally reduce the FTP cycle only, and that which not just reduces the FTP cycle emissions but also

[5] Southwest Research Institute (SwRI) data on today's engines yield a 0.35 to 1.5 g/bhp-hr emissions NO_x on the LLC, compared to the certification requirement of a 0.2 g/bhp-hr on the FTP (and thus < 0.2 g/bhp-hr test values).

closes the gap between hot- and cold-start emissions, reducing the disparity between the FTP and LLC tests (Table 1).

Implementing an LLC nationally yields an additional 8 percent reduction in real-world NO_x emissions in 2035 (Figure 3) by forcing more reduction under the low-load operation responsible for a disproportionate share of NO_x emissions.

C. Extending the Warranty and Lifetime for Emissions Control

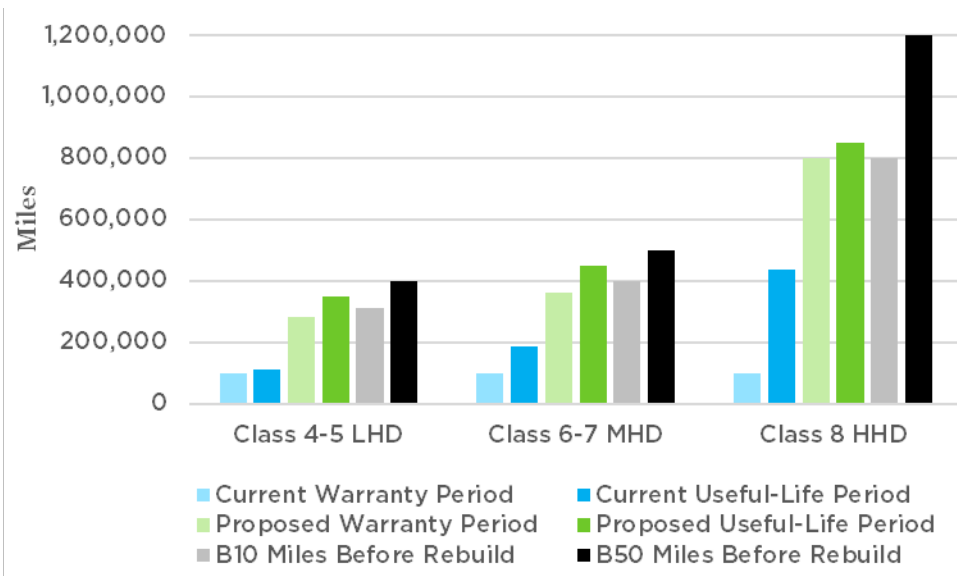
We intend to propose new useful life mileage values for all categories of heavy-duty engines to be more reflective of real-world usage. (85 FR 3323)

We intend to propose longer emissions warranty periods. (85 FR 3324)

Heavy-duty diesel engines last well beyond the current useful lifetime, with 90 percent of engines lasting nearly double the current regulatory requirement, and 50 percent of Class 8 engines nearly triple (Figure 4). This extends to the warranty period, where the standard 100,000-mile warranty requirement is only a very small fraction of the expected lifetime of the engine and is well behind typical warranties and extended warranties of 250,000 and 500,000 miles (CARB 2017).

The useful life is critical to ensure adequate testing such that emissions controls are functional for the life of the engine. The warranty period, however, is more important to minimize tampering or

FIGURE 4. Engine warranty and useful-life periods, compared to average rebuild mileage



Heavy-duty engines can last up to 1.2 million miles before a rebuild, yet the current warranty extends to just 100,000 miles, and the useful-life period is only 435,000 miles. The CARB proposed changes to the warranty and useful-life periods for heavy-duty vehicles more closely mirrors the real-world operation of these engines and would help maintain working emissions controls while diminishing any costs incurred by the operators.

SOURCES: CARB 2017, CARB 2019C

disrepair and shifts the cost of failures onto the manufacturer rather than the driver. Repair costs and downtime can be a significant burden for drivers, and survey data has shown that there is a significant interest in coverage that better reflects the operational lifetime of the vehicle (Kerschner and Barker 2017). Nearly one-quarter of respondents already opt for an extended warranty, with a substantial share of those respondents choosing warranties that exceed the current useful-life requirements of the engine. A majority of owner-operators suggested future warranty coverage should meet or exceed 500,000 miles, well above the current minimum.

We modeled the benefits of the warranty and lifetime changes using the same approach as the MOVES model (EPA 2015), updating the respective lifetimes for the appropriate model years (CARB 2019c). Because our modeling looks at 2035, only 2027 model year vehicles and later yield any improvement, diminishing the potential overall level of improvement that could result as vehicles with these significantly extended warranties are put into service.[6] We have assumed the same level of degradation/mal-maintenance for 2024- and 2027-compliant engines as 2010-compliant engines.

According to our analysis, the extended lifetime and warranty result in an additional 2 percent reduction in NO_x and direct $PM_{2.5}$ emissions in 2035.

D. Reduction of the $PM_{2.5}$ standard

We request comment on the need for more stringent PM standards for heavy-duty gasoline engines. (85 FR 3318)

Diesel particulate filters (DPFs) have allowed for manufacturers to reduce $PM_{2.5}$ emissions well below the current regulatory target. Furthermore, work at SwRI shows the potential for even further reductions in $PM_{2.5}$ emissions (CARB 2019e). Some manufacturers may choose to reduce backpressure on the engine by reducing the size/efficiency of the DPF, particularly as CARB and EPA move forward with more stringent NO_x regulations. It is imperative that as part of the CTI regulation that EPA reduce the current engine target for $PM_{2.5}$ as well as NO_x, so that EPA does not inadvertently allow the industry to backslide, increasing the direct tailpipe emissions of $PM_{2.5}$.

The vast majority of engine families today have certified test values of 0.005 g/bhp-hr or better (EPA 2020), so EPA could reduce the current PM2.5 certification value with little impact on the industry, while limiting backsliding. Furthermore, as part of this rulemaking, EPA should explore the potential for a particle count standard--current Euro VI standards also include a particle number limit as part of their test procedures (Rodriguez and Posada 2019), and the unique health ramifications of ultrafine particles (Section I.B.) in addition to the impacts that black carbon particle size has on climate (Matsui et al. 2018) suggest that there is a current need for the regulation of particle ***number*** in addition to mass.

It is appropriate for EPA to adopt an equally stringent PM standard for gasoline engines. Gasoline particulate filters (GPFs) are available today and would be able to achieve the same level of reductions found today with DPFs (MECA 2013). GPFs are already being deployed in the light-duty

[6] CARB has also proposed increases to warranty coverage for MHD and HHD engines beginning in 2022 (to 150,000 and 350,000 miles, respectively), but vehicles sold with such engines will have exceeded warranty coverage by 2035 and thus do not contribute at all to the modeled emissions reductions.

vehicle fleet in order to comply with more stringent European regulations (Giechaskiel et al. 2019)—in the spirit of technology neutrality, and with no technological barrier, it would be appropriate to set a PM standard for gasoline engines equivalent to their diesel counterparts.

E. Glider Vehicles

III.D.2. Tamper-Resistant Electronic Controls (85 FR 3325), ***III.D.4. Emission Controls Education and Incentives***, and ***III.D.5. Improving Engine Rebuilding Practices*** (85 FR 3327)

EPA notes in the CTI ANPRM a number of avenues to minimize the tampering, removal, or bypass of emissions control equipment and strategies to ensure that the industry maintain good maintenance practices consistent with upholding the required reductions over the lifetime of the vehicle. At the same time as it is proposing a number of much needed initiatives targeting the avoidance of emissions controls, it has not addressed the elephant in the room—the agency has proposed re-opening a loophole for glider trucks, which would advance the growth of a cottage industry designed to do exactly what EPA says it is trying to limit, which is to bypass modern diesel emissions control systems.

Glider trucks are new vehicle "shells", in which an older engine is added. While historically these vehicles were used exclusively in cases where a vehicle was damaged beyond repair early in the diesel engine's lifetime, a cottage industry sprung up after the institution of the 2007/2010 emissions standards acquiring pre-2007 engines to sell the vehicles as a heavily polluting alternative to the new, cleaner diesel vehicles, with emissions up to 40 times higher than today's vehicles.

In the 2018-2027 Greenhouse Gas Emissions and Fuel Economy Standards for Medium- and Heavy-duty Engines and Vehicles ("Phase 2 rule"), EPA instituted new requirements for glider trucks, including a cap limiting glider truck sales to the lesser of 300 vehicles or the maximum number of vehicles sold annually from 2010-2014. This was designed to curtail the industry's growth, which had grown to around 10,000 vehicles sold each year, while still recognizing the legitimate need for gliders that predated the 2007/2010 emissions regulations.

EPA estimated that glider sales under the Phase 2 "cap" would be limited to about 1500 per year; however, data from 2018, the first year with this limit, were approximately 3500, a significant increase.[7] According to EPA's estimates, every glider truck on the road in a given year would emit a whopping 4,583 pounds of NO_x per year and 121 tons of $PM_{2.5}$ per year—in 2040, at annual sales of 10,000 per year, EPA staff estimated that this would result in 318,615 tons NOx and 8,546 tons PM2.5, more than 6 times larger than with no gliders whatsoever.

While the cap instituted by EPA has cut the apparent production of gliders by two-thirds, the disproportionately high emissions from these vehicles is at cross purposes to the CTI and should be addressed in the CTI NPRM. We estimate that if 2018 sales of glider vehicles persist, by 2035 they will represent 8 percent of total NO_x emissions and 25 percent of $PM_{2.5}$ emissions from heavy-duty diesel vehicles—the agency doing nothing to mitigate such an egregious problem in a rulemaking aimed to reduce pollution from heavy-duty trucks would be patently absurd.

California's Truck and Bus Regulation restricts heavy-duty fleets operating in the state from using vehicles with engines older than the 2010 model year, beginning in 2023 and phased in over the

[7] Personal communication with EPA OTAQ technical staff.

next three years. If EPA were to similarly require that engines installed in glider vehicles beginning in 2027 meet the 2007/2010 standards, this would cut NO_x emissions in 2035 by an additional 10 percent and would cut direct $PM_{2.5}$ emissions from HDVs by 13 percent.[8]

F. Idle emission standard

We request comment on the need or appropriateness of setting a federal idle standard for diesel engines. (85 FR 3321)

Beginning in 2008, California required new trucks sold in the state to meet a "Clean Idle" standard. There are two means by which a truck can be certified to the standard, either by having an automatic shut-off that cuts the engine after five minutes of idling, or by meeting a 30 g/hr NO_x idling standard. All heavy-duty engines in 2019 and 2020 comply with the standard by meeting the 30 g/hr requirement (CARB 2020a). Though this standard was implemented only in California, it has driven 50-state improvements, with EPA's in-use data showing that the vast majority of diesel engines meet the 30 g/hr threshold (Badshah et al. 2019 [Figure 13]).

Because in-use data shows a higher fraction of idling than current test procedures, and because this has already proven to drive idling emissions downward, EPA should consider implemented an idling standard that goes beyond the current 30 g/hr. CARB has proposed a 10 g/hr idle standard, beginning in 2024, and it has signaled the possibility of a further reduction in the idle standard in 2027. However, even this reduced standard does not currently reflect the increased availability of stop-start and zero-emission technologies, which CARB's idle rule was initially anticipated to promote (Chen 2008).

EPA should evaluate the additional benefits of an idle standard, including the promotion of non-diesel technologies. Part of that evaluation should be consideration of flexibilities or incentives designed to eliminate idling emissions entirely.

Our modeled compliance with the LLC standard proposed by CARB itself was able to achieve the 10 g/hr proposed standard, so we were unable to estimate only the benefits of a stronger idle emissions program. However, even at the proposed 2024 targets of 0.05 g/bhp-hr FTP and 0.2 g/bhp-hr LLC, the emissions from an average engine only barely met the 10 g/hr standard, thus indicating that some engines likely would have exceeded this standard (it is an average, afterall). Therefore, it is likely that a hard limit could result in additional emissions reductions, depending upon the absolute levels of the proposed standards and whether a binding low-load cycle target was also incorporated into the standard.

G. In-use testing

We request comment on the potential use of telematics and communication technology in ensuring in-use emissions compliance. (85 FR 3328)

We strongly support the use of telematics to identify trucks which are emitting at inappropriately high levels, and we encourage industry to work together with CARB and EPA to develop an approach which

[8] A similar level of improvement would be achieved if EPA gradually phased out glider sales entirely by 2035.

can remove those vehicles off the road as quickly as possible to be serviced for malmaintenance and/or identified for enforcement of anti-tampering regulations as appropriate.

While telematics can be a useful tool for in-use compliance, we are concerned about proposals raised by industry which suggested the use of telematics as a way that effectively becomes a defeat device—namely, it was proposed that within certain "geofenced" areas, the truck would operate at an ultralow NOx emissions rate, while in other areas of the country the truck would operate with higher NO_x emissions and higher fuel economy. As identified in Section III, technology exists which can simultaneously reduce NO_x and greenhouse gas emissions. It is inappropriate that an internal combustion engine be allowed operate in a more highly polluting mode simply based on where it is currently located. Not only would this raise a whole host of equity issues, unnecessarily, but there are additional serious concerns about enforcement and tampering that would be raised around such a strategy, which essentially amounts to a defeat device.

EPA intends the CTI to expand our in-use procedures to capture nearly all real-world operation. We are considering an approach similar to the European in-use program, with key distinctions that improve upon the Euro VI approach. (85 FR 3322)

As EPA notes, the current heavy-duty in-use testing (HDIUT) requirements are woefully inadequate—the vast majority of data are discarded due the very narrow NTE window and limits on aftertreatment temperature, which all but neglect low-load operations, where aftertreatement systems are frequently operating below light-off conditions (Section II.B). It is critical that any HDIUT program accurately reflect the typical range of operating conditions that a truck undergoes, in order to ensure the lab certification tests continue to drive the anticipated emissions reductions.

When shifting to a Moving Average Window (MAW) approach, we concur with the ICCT that any HDIUT program should include all data, with a focus on ensuring that low-load operation is captured (Rodriguez and Posada 2019). We are concerned that EPA's approach to characterize the low-load lower bound/idle upper bound by the normalized average CO2 rate of the LLC (85 FR 3322) could shift too much low-load operation to the "idle" category, thus artificially easing requirements under the low-load conditions which are currently inadequately captured by current HDIUT requirements.

Regardless of the approach taken by EPA in its CTI NPRM, we would hope that the agency provide the results of its MAW approach applied to its current HDIUT program and/or a sufficiently representative set of real-world vehicle data, to clearly indicate the ranges of operation for its MAW bins were they to have been applied to today's trucks.

H. <u>Changes to current test procedure based on Phase 2 rulemaking</u>

Based on its work for the Phase 2 regulation, EPA adopted a number of test procedure changes which are applicable to the CTI program. While we speak to the specific changes proposed by EPA below, one overarching principle must be clear—any change in test procedures must also be used to reset the respective baselines, in order to avoid any "paper" emissions improvements.

1. Changes to the FTP test

We are considering changes to the weighting factors for the FTP cycle for heavy-duty engines. (85 FR 3320)

Narrowing the discrepancy between cold-start and hot-start emissions is a key factor in reducing future NO_x emissions from heavy-duty trucks. As described in Section II.B, real-world data on heavy-duty vehicles shows a substantial fraction of operation under conditions where the emissions control system is operating well below optimal efficiency. A recent analysis showed that while the share of cold-start operation was consistent with the current FTP share, that only a fraction of the remaining starts could be characterized as "hot" (Zhang et al. 2019). Of particular note in this analysis is the exclusion of any "engine-off" periods in the FTP test, which is inconsistent with real-world driving conditions, and the exclusion of "warm-start" operations.

The current FTP test could be improved to better reflect real-world operation. Any such improvements must be considered when assessing the level of improvements from today's baseline technologies.

2. Changes to the RMC test

We adopted new RMC weighting factors for CO_2 emissions in the Phase 2 final rule (81 FR 73550, October 25, 2016). Since we believe these new weighting factors better reflect in-use operation of current and future heavy-duty engines, we request comment on applying these new weighting factors for NO_x and other criteria pollutants as well. (85 FR 3321)

Engines today are significantly downsped relative to when the RMC test was originally developed, and that downspeeding trend is expected to continue, as EPA noted. This trend is why we supported EPA's reweighting of the RMC in the Phase 2 regulations and recommended that the agency correct the disparity in a future NO_x rulemaking (Cooke 2015). However, EPA did not adequately consider the impact of the reweighted cycle on emissions from the baseline engine, and therefore left significant improvement on the table (Cooke 2015 [Table 1]).

EPA should align the RMC cycle used in NOx and criteria pollutant testing with that used in the Phase 2 rule, but they should not repeat the error made in Phase 2 of not appropriately characterizing the current state of technology on this revised test procedure.

3. Powertrain testing

Stakeholders previously expressed concern that the engine-focused certification process for criteria pollutant emissions does not provide a pathway for hybrid powertrains to demonstrate NO_x reductions from hybrid operations during certification. As such, we plan to propose an update to our powertrain test procedure for hybrids, previously developed as part of the HD Phase 2 rulemaking for greenhouse gas emissions, so that it can be applied to criteria pollutant certification.[83] [84] (85 FR 3319)

UCS was supportive of the powertrain test procedure introduced in the Phase 2 regulation due to its ability to capture a systems-level approach to fuel consumption reduction. Given the abundance of technologies identified and the way in which many of these systems could interact synergistically to yield reductions in NOx emissions, it seems appropriate to adapt the powertrain test to the NO_x test program. There has been a significant amount of data collected by CARB as part of its own hybrid certification program, and we urge the agency to take advantage of this dataset in developing an appropriate powertrain test procedure, including OBD and HDIUT requirements. This is especially important for hybrid and plug-in hybrid vehicles, where the engine may be shut off for much longer periods of time and/or undergo a significantly higher share of cold starts.

III. Technology availability and potential

Because CARB has spent years developing its regulation, there is a significant amount of research available about technologies which could achieve a 0.02 g/bhp-hr standard on the FTP cycle. Of particular note is the significant number of developments that have occurred over the past couple years that show technologies like cylinder deactivation which were excluded from the Phase 2 rulemaking but can simultaneously reduce both NO_x emissions and fuel use/greenhouse gas emissions. We respond to EPA's specific technology questions below.

A. SCR catalyst development

We request comment on the extent to which advanced catalyst formulations can be used to lower emissions further, and whether they would have any potential impact on CO2 emissions (85 FR 3313).

Copper-based zeolite systems dominate the market today and continue to improve. Cu-zeolites have an advantage over iron (Fe) due to a lower light-off temperature and the ability to deal with a wider range of NO_x/NO_2 ratios—however, under certain transient conditions, Fe-zeolites can perform even better (Kamasumudram et al. 2010), and as temperatures increase, Cu-zeolites begin to decrease efficiency. Moving forward, combined systems utilizing both Cu- and Fe-zeolite could provide the best of both worlds (Girard et al. 2008), better allowing for novel packaging strategies which might be exposed to greater temperature differentials (Section III.B).

In a recent study, MECA compared previous catalyst performance to current catalysts as well as a next-generation system as part of its study of aftertreatment technologies available in the 2024 timeframe (MECA 2019). Improving the catalyst alone from 2014 to 2019 technology cut hot-start FTP NO_x emissions by two-thirds, even while using the same emissions control design. Improvements enabled by next-generation catalysts (including the potential for a second, smaller, upstream SCR system) were able to further reduce the hot-start NOx emissions below 0.02 g/bhp-hr, while also significantly reducing N_2O, a greenhouse gas for which EPA has already instituted a cap.[9]

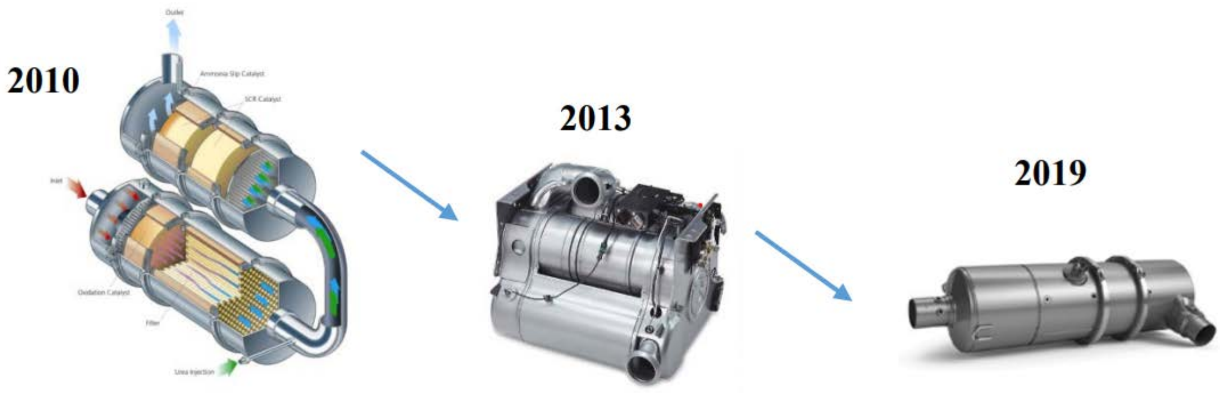
Improvements in substrate design have improved the ability for SCR systems to reduce NO_x emissions, and these trends are likely to continue. For example, recent advances in the honeycomb design have allowed for increase loading (MECA 2019). A benefit of this is the ability for the system to shrink in size (see Section III.B) and reduce the backpressure on the engine, which thus improves fuel efficiency and reduces CO_2 emissions.

Additional progress is also being made in regards to durability, a factor which is critical for novel aftertreatment designs such as a dual-SCR system (see Section III.B). For example, a second-generation Cu-zeolite SCR showed less than a 10 percent deterioration in performance after accelerated aging at high temperatures, as compared to a 40 percent deterioration in performance in the current generation (MECA 2019).

---

[9] In fact, these N_2O reductions are significant enough that they would be eligible for credit under the Phase 2 program, showing that a well-designed aftertreatment can actually ***cut*** greenhouse gas emissions.

FIGURE 5. Aftertreatment system packaging over time



Packaging of SCR systems has changed dramatically over the past decade, moving to a much more compact configuration that is 60% smaller, 40% lighter, and significantly less expensive. This more compact design allows for novel strategies for future aftertreatment systems, including close-coupled dual-SCR.

SOURCE: MECA 2019

B. Aftertreatment packaging and system design

EPA is evaluating this dual-SCR catalyst system technology as part of our diesel technology feasibility demonstration program. (85 FR 3315)

We welcome comment on active thermal management strategies, including any available data on the cost, effectiveness, and limitations, as well as information about its projected use for the 2024 to 2030 timeframe. (85 FR 3314)

Packaging of SCR systems has changed dramatically over the past decade, moving to a much more compact configuration that is 60% smaller, 40% lighter, and significantly less expensive (MECA 2019). This evolution in packaging has been enabled through improvements to catalyst substrate design which allow for improved catalyst loading, efficiency, and durability (see Section III.A). Because of the substantial progress to date, there is room in the vehicle for an evolutionary step to more sophisticated systems.

One of the primary challenges noted by EPA around continued improvement in low-load operations, particularly in reducing the amount of time before effective catalytic reduction. Reducing the thermal mass of the SCR systems and better insulation of the exhaust system can help reduce the warm-up time and maintain the temperature of the system through transient operation, and example of passive thermal management—this was exactly the strategy represented in our modeling (Section II).

There are also active approaches to thermal management, such as efficient fuel-based "burners" or electric heaters to heat the exhaust, but these can have the negative impact of requiring additional fuel use. Rather than actively heating the exhaust gas, there is also the possibility of heated dosing. In this case, the urea itself is heated when atomized, which can allow for NOx conversion at lower temperatures (Sharp et al. 2017). Conversely, there is an alternative approach where the catalyst itself is heated, improving reactivity to such an extent that the system can be reduced in volume by 50 percent while seeing an improvement on the FTP cycle of 60 percent (Bruck et al. 2018). While these designs all require additional energy to improve NOx reduction, there is a wide range of fueling impacts, indicating that there may be appropriate levels representing a "sweet spot" for optimal NOx reduction with minimum GHG increase (Sharp 2017).

An alternative approach combining theories behind the active and passive approaches is the use of a second SCR system positioned upstream in a dual-SCR configuration. Also known as "light-off" SCR, this smaller SCR unit is more closely coupled thermally to the engine and has reduced thermal mass, allowing it to achieve light-off temperature much more quickly than a traditional SCR system. Because this reduces the thermal inertia downstream, at high-load conditions where a close-coupled Cu-zeolite may be less efficient (due to temperatures greater than 350°C) in the first SCR, the second SCR system could thus be in the optimal zone. Such a system requires more complex controls strategies (Kasab et al. 2019), but such operation could significantly improve aftertreatment efficiency, particularly at low load.

Early results from the dual-SCR system are promising, showing both reduced impact on greenhouse gases and achieving nearly a 0.02 g/bhp-hr standard on the FTP cycle (Sharp 2017). Of particular note regarding EPA's concern about N_2O is that the dual-SCR system exhibited lower N_2O emissions because the system is upstream from the passive catalysts (Sharp 2017 [213]). These findings were affirmed in more recent (but not yet finalized) research using a 2017-compiant, non-turbocompounding engine (Sharp 2019).

While the Stage 1 SwRI study was unable to fully integrate and optimized dual-SCR system, we concur with CARB staff that such technology is viable in the 2024 timeframe, with low greenhouse gas penalty (CARB 2019e). Continued development and refinement of this system is likely to lead to even lower reductions beyond the significant low-temperature improvements already exhibited.

EPA's proposed research (85 FR 3315) would be a critical addition to assessing any questions about durability with the system, which would be an important data point in assessing the technology's viability in the near-term. However, Volkswagen has already introduced a dual-SCR system in its diesel-powered light-duty vehicles (VW 2019), and Cummins is already implementing a close-coupled SCR right now (Kasab et al. 2019), suggesting that such concerns may be overblown.

C. Engine-based strategies

In addition to upgrades to the aftertreatment system, it is possible to reduce NOx emissions at the source by driving improvements to the engine itself. These systems changes are complementary to different aftertreatment designs and are a key approach to reducing greenhouse gas and NOx emissions simultaneously.

1. Turbocharger and EGR improvements

Exhaust flow bypass systems can be used to manage the cooling of exhaust during cold start and low load operating conditions. For example, significant heat loss occurs as the exhaust gases flow through the turbocharger turbine. Turbine bypass valves allow exhaust gas to bypass the turbine and avoid this heat loss at low loads when turbocharging requirements are low. In addition, an EGR flow bypass valve would allow exhaust gases to bypass the EGR cooler when it is not required. (85 FR 3314)

As noted in the Phase 1 SwRI work, turbocompounding can be a useful technology for meeting future fuel economy and greenhouse gas targets (Sharp 2017); however, it also has the challenge of reducing the temperature of the exhaust gas, which would thus increase the challenges of low-load operation of aftertreatment systems.

One strategy to deal with this challenge is to directly route the exhaust gases to the aftertreatment system, bypassing the turbo under cold-start conditions. This strategy alone can yield nearly a 50°C increase in temperature for the aftertreatment system within the first 100 seconds of cold-start operation, allowing the system to operate at 60 percent NO_x conversion (MECA 2020 [12]).

An alternative strategy, which can also help with fuel efficiency, is to deploy either a mechanically or electrically driven turbo, which can thus decouple exhaust gas recirculation (EGR) from boost (MECA 2020 [13]). One supplier claims that one such system going into production in 2021 can contribute to a 20 percent reduction in NO_x emissions (Abuelsamid 2019). Another approach to breaking this current mechanical link between boost and EGR is with an EGR recirculation pump (Park 2019). As noted in Eaton's description of the technology, such a pump can be used in other advanced strategies to simultaneously reduce NOx and CO2 emissions, including 48V electrification and variable valve actuation (VVA) (Eaton 2020). This product was shown, when combined with a higher-efficiency fixed geometry turbocharger, to reduce emissions while improving brake specific fuel consumption (BSFC) by up to 5 percent (McCarthy 2019a).

2. Variable valve actuation

We welcome comment on CDA and LIVC strategies for NO_x reduction, including any available data on the cost, effectiveness, and technology limitations. (85 FR 3314)

For light-duty vehicles, VVA has been used for decades to reduce fuel use, but recent advances in controls have allowed for new efficiency strategies like part-time Atkinson and Miller cycles. VVA strategies for heavy-duty vehicles can build on those controls advancements to develop novel diesel valve control that can fine-tune intake/exhaust valve timing to reduce emissions and fuel use at the same time.

Early exhaust valve opening (EEVO) is one example of a strategy to utilize VVA in an effort to reduce emissions (e.g., Honardar et al. 2011, Roberts et al. 2015). In this case, the exhaust valve is opened before completing the power stroke, which can thus significantly increase exhaust temperature, albeit at the expense of increased fuel use, and in some cases with trade-offs on other pollutants (HC, CO, $PM_{2.5}$). Careful optimization is key to this approach and can be improved through more advanced controls (Salehi and Stefanopolou 2018). With such advanced controls in place, VVA can be used to compensate for any fuel penalty from EEVO through improved efficiency, such as early and late intake valve closing (EIVC, LIVC)—such strategy can even be used to implement Miller cycle operation in the diesel engine. A forthcoming analysis as part of the Volvo SuperTruck program shows that Miller cycle operation can enable reduced NO_x emissions without compromising on efficiency (Garcia et al. 2020).

One particular VVA strategy which helps both reduce fuel and address low-load emissions is cylinder deactivation (CDA). CDA has already been proven effective and durable in light-duty vehicles, but recent research shows the strong benefits of CDA in heavy-duty diesel vehicles as well. CDA essentially allows the engine to be downsized in real time—this has the effect of dramatically increasing temperature of low load operation (about 100°C in an MHD engine) while improving overall fuel efficiency (McCarthy 2019b). Importantly, this study found fuel savings (3.2 to 7.8 percent) and NOx reduction (33 to 86 percent) over a range of real-world driving cycles emphasizing low load operation, without any modification to the production aftertreatment system. Even at low-load operation and idle conditions, heavy-duty CDA saw increases of 60-80°C with fuel savings of 8 to 28 percent (McCarthy 2019a). This same study also showed improvements for DPF regeneration and showed how dif

EPA specifically noted concerns about noise, vibration, and harshness (NVH)(85 FR 3314) with CDA; however, recent data shows that careful systems optimization can identify any resonant modes and compensate (Neely et al. 2019). This recent work out of the SwRI Phase 3 project shows that CDA, combined with an improved aftertreatment system, can achieve 96 percent NO_x conversion on the LLC while reducing FTP emissions below 0.02 g/bhp-hr, all the while saving fuel.

D. Alternative powertrains

Some of the same advances made in light-duty electrification are proving transferrable to heavy-duty vehicles, including mild 48V hybridization and plug-in electric vehicles, which are discussed in more detail below. These technologies offer the potential for significant reductions in both greenhouse gas and NOx and PM2.5 emissions, but because their improvements are not limited to the engine, it will be important to develop test procedures and crediting that reflect the full benefits of these technologies (e.g., Section II.H.3).

1. Hybridization

Full-hybrid electric trucks have been in the heavy-duty market for quite some time, both fully integrated by the OEM (e.g., Eaton, BAE Systems) and in the aftermarket (e.g., XL Hybrids, Odyne). However, the high upfront cost of many of these systems has led to limited penetration of hybrid technology primarily to duty cycles with high idle fractions and lots of stop-start operation, where the total cost of ownership (TCO) makes the clearest case.

Mild hybridization can offer a lower cost opportunity, particularly with a movement towards 48V electrification. Higher voltage allows for more efficient power distribution, and shifting the number of hydraulically or mechanically driven accessories to electric operation has benefits not just for efficiency but also packaging of the engine compartment. A 48V mild hybrid system simply builds upon these already existing rationale for moving to a 48V electric system and uses it for better regenerative braking and more responsive stop-start.

Many of the strategies mentioned in Section III.C would benefit from 48V mild hybridization—for example, a 48V electrical system is an enabler for devices like an electrically driven turbocharger (MECA 2020), an electrically heated catalyst (Dorobantu 2019), or an electrified EGR pump (McCarthy 2019a).

One analysis projected that 48V systems in line-haul operation would cost less than $7,000 for up to 4 percent fuel savings in 2025 (Tarnutzer 2017). A recent report by the National Academies estimated 2022 costs for a 48V mild hybrid system to range from $4,584-5,010 (Class 4) up to $10,080-11,700 (Class 8 vocational), noting that “costs will likely come down in the 2022 and 2030 time frames,” with fuel savings ranging from 16-22 percent depending on the duty cycle (NRC 2019). These costs are substantially reduced compared to those previously used by EPA (Phase 2 RIA p 2-175).

2. Battery electric vehicles

State and local activities, such as the Advanced Clean Trucks rulemaking underway in California could also influence the market trajectory for battery-electric and fuel cell technologies.82 EPA requests comment on the likely market trajectory for advanced powertrain technologies in the 2020 through 2045 timeframe. (85 FR 3319)

A) ELECTRIC VEHICLE AVAILABILITY

As of November 2019, there were 27 different manufacturers with 70 different models of zero-emission trucks and buses available today or within the next two years (O'Dea 2019). Battery and fuel cell electric offerings span Class 2b to Class 8 trucks and buses and include vehicles from new entrants such as Proterra, Tesla, BYD, and Rivian to established OEMs such as Daimler, Volvo, and Navistar.

Many electric trucks are on the road or on order. As of October 2019, California's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) has awarded vouchers for the purchase of 2,700 zero-emission trucks and buses across many different vehicle categories (Table 2).

TABLE 2. Number of zero-emission vouchers approved by vehicle type via incentives

Number of Zero-Emission Vouchers Approved by Vehicle Type supported by California's HVIP incentive funding	
Tractor Trailer	1
Yard Tractor	208
Transit Bus	542
School Bus	183
Shuttle Bus	133
Coach Bus	44
Delivery Truck	1589
Refuse Truck	2
Utility Truck	9
Other Truck	1
Total	**2712**

Plug-in electric vehicles are already available in a wide range of heavy-duty body types and applications. Current incentives are helping to drive market adoption and will help accelerate technology development in advance of EPA's 2027 rule timeframe.

Note: HVIP = Hybrid and zero-emission truck and bus Voucher Incentive Program

SOURCE: PRIVATE COMMUNICATION WITH CARB TECHNICAL STAFF

Future vehicle availability includes the electric pickup trucks. Tesla has indicated its Cybertruck, for which there have been over 250,000 pre-orders, will be in the Class 2b weight category (Van Cleve 2019). Electric pickup trucks have been announced six other manufacturers including Ford (F-150), GM (Hummer EV), Rivian (R1T), Bollinger (B2), Lordstown (Endurance), although weight categories are not known for these vehicles.

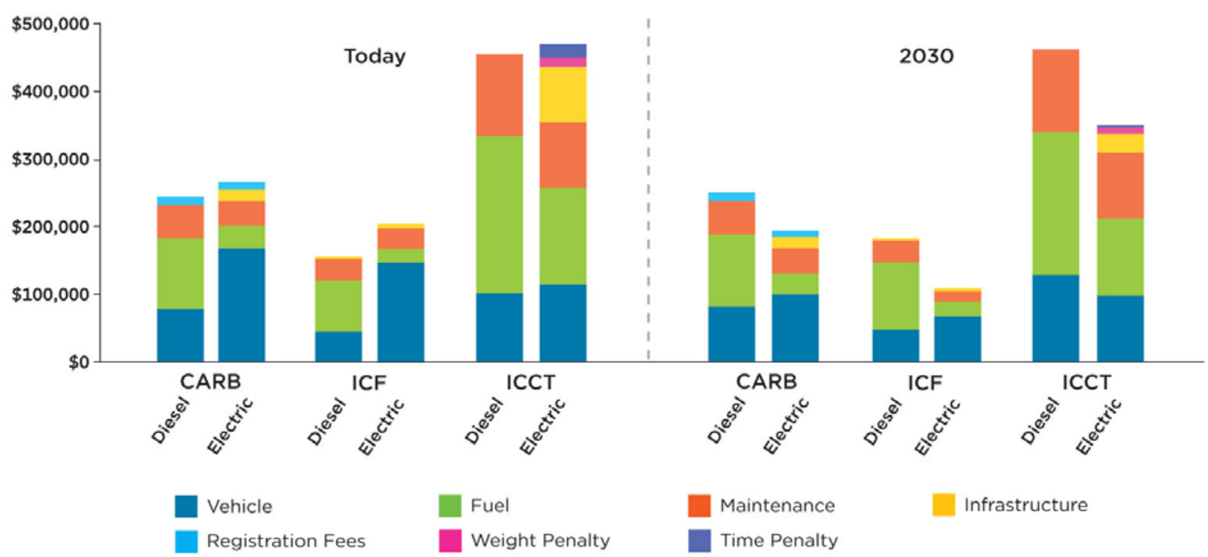
Furthermore, BYD has already delivered 100 electric trucks to customers in the US (BYD 2020), and both Volvo and Daimler are currently testing battery electric Class 8 trucks in regional applications in Southern California (Hirsch 2019). Volvo announced their electric truck will be available for purchase by the end of 2020 (Cullen 2019).

B) FAVORABLE ECONOMICS OF ELECTRIC TRUCKS AND BUSES

Several analyses have found that the total cost of ownership of battery electric trucks and buses is becoming increasingly competitive with comparable diesel vehicles due to significant savings on fuel, which offset higher vehicle costs (CARB 2019f; Hall and Lutsey 2019; ICF n.d.; Phadke et al. 2019). Within the next 10 years, many studies predict significant savings on a total cost of ownership basis for electric trucks and buses compared to diesel and natural gas. For example, Figures 5 and 6 show total cost of ownership findings for vehicles purchased today and in 2030 from three studies examining costs associated with delivery trucks and regional Class 8 tractors, respectively.

Results shown in these figures are based on electricity and fuel prices in California and do not include any of the state's significant financial incentives that offset the costs of vehicle purchases, fuel, and charging infrastructure. California's Low Carbon Fuel Standard, which financially penalizes fuels with carbon intensities above a set standard and rewards fuels below it, can lower the electricity rates for heavy-duty vehicles approximately \$0.09 to \$0.14 per kWh today and \$0.07 to \$0.12 per kWh in

FIGURE 5. Total Cost Comparisons, Class 6 Delivery Trucks

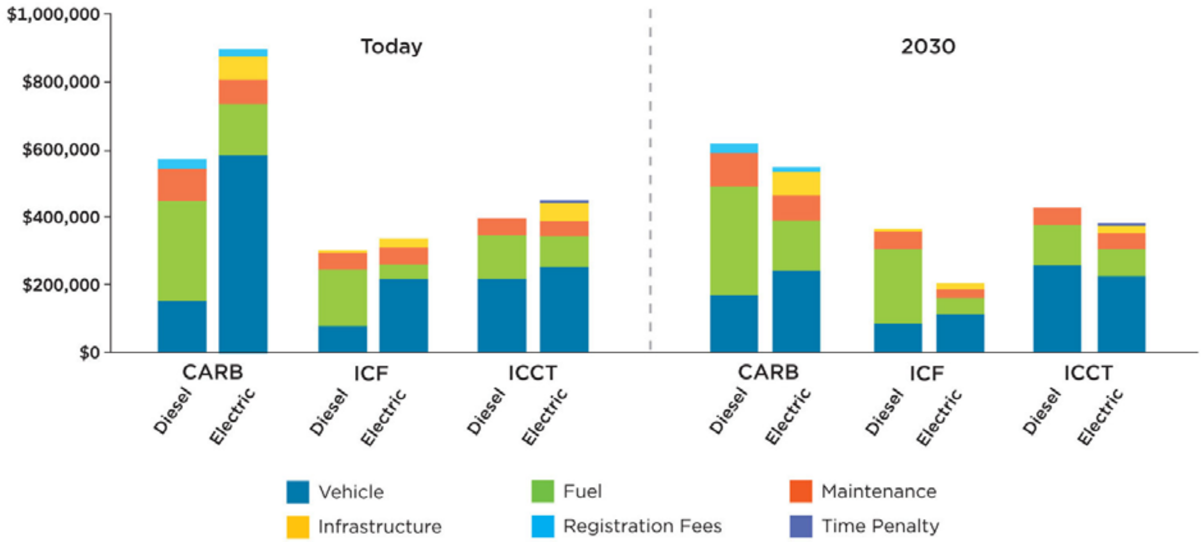


The total cost of ownership for Class 6 electric delivery trucks is competitive with diesel vehicles today and estimated to be significantly lower within the next decade.

Notes: In the ICCT study, "today" corresponds to 2020; in the CARB and ICF studies, 2018. Vehicle costs in the ICF and CARB analyses account for the residual value of the vehicle at the end of its assumed period of ownership.

SOURCE: O'DEA 2019

FIGURE 6. Total Cost Comparisons, Class 8 Short-Haul/Drayage Trucks



The total cost of ownership for Class 8 electric short-haul/drayage trucks can be lower than diesel today with financial incentives, and is estimated to be lower for diesel trucks within the next decade without such incentives.

Notes: In the ICCT study, "today" corresponds to 2020; in the CARB and ICF studies, 2018. Vehicle costs in the ICF and CARB analyses account for the residual value of the vehicle at the end of its assumed period of ownership.

SOURCE: O'DEA 2019

2030, depending on the fuel efficiency improvements of an electric vehicle compared with a diesel vehicle, further lowering the total costs of ownership compared to what are shown in Figures 5 and 6.[10]

In a recent September 2019 analysis of long-haul battery electric trucks, researchers at the Lawrence Berkeley National Laboratory concluded:

> "We estimate the TCO of an electric truck to be $1.27/mile, 20% less than that of a diesel truck, assuming trucks can access average industrial electricity prices of about $0.07/kWh which require reforms in electricity tariffs to make demand and transmission charges peak-coincident. We find that if environmental externalities, such as air pollution and greenhouse gas emissions are monetizable, the TCO of an electric truck could be as low as $0.95/mile, 40% lower than a diesel truck." (Phadke et al. 2019)

In another recent study (October 2019) of zero-emission drayage trucks at the San Pedro Bay Ports the UCLA Luskin Center for Innovation concluded:

[10] Estimates of Low Carbon Fuel Standard revenues use credit values of $100 per metric ton of CO_2e and a carbon intensity of electricity in California of 93.11 grams CO_2e per megajoule (MJ) in 2019 (based on the California Energy Commission's grid mix for 2019), and 54.43 grams CO_2e per MJ in 2030 (based on the California Public Utilities Commission's Integrated Resource Plan).

> "BETs [battery electric trucks] can be financially viable in the 2020s. With purchase incentives, the total cost of ownership for BETs in both LADWP [Los Angeles Department of Water and Power] and SCE [Southern California Edison] territory are lower than even the cost of used diesel trucks." (Di Filippo et al. 2019)

C) POLICY SIGNALS FOR ELECTRIFICATION

Significant activities around heavy-duty vehicle electrification are underway, particularly in California through CARB standards, but also nationally as states begin disbursing funding for electric trucks and buses through the Volkswagen Diesel Emissions Environmental Mitigation Trust and the Federal Transit Administration's Low or No Emission Vehicle Program, which provides funding for zero-emission transit buses (FTA 2020). National actions on zero-emission trucks and buses include 8 states and the District of Columbia committing to the development of a multi-state memorandum of understanding to support and accelerate the deployment of medium- and heavy-duty ZEVs through a collaborative process facilitated by the Northeast States for Coordinated Air Use Management (NESCAUM 2019).

Through a series of legislative and regulatory measures, California intends to establish, if not already established, legal requirements for the deployment of electric trucks and buses.

CARB is nearing the finalization of the Advanced Clean Trucks Rule, which will establish zero-emission vehicle manufacturing standards for OEMs selling trucks in California, similar to the existing Zero-Emission Vehicle policy for the manufacture of light-duty zero-emission vehicles. CARB has indicated a final vote on this regulation will occur in May of this year. As currently drafted (CARB 2019g), the proposed regulation would result in electrification of at least 4 percent of California's on-road Class 2b-8 truck population by 2030. At a December 2019 CARB Board Meeting, Board Members provided direction for the proposed standards to be strengthened before the final vote.

CARB has also begun the public workshop process for the Advanced Clean Fleet standard (CARB 2020b), which would set standards for fleets to purchase electric trucks and buses, similar to policies already in place for transit and airport shuttle fleets. The former requires 100 percent of transit buses sold in California to be zero-emission vehicles by 2029 and the latter requires 100 percent of airport shuttle buses serving the state's 13 largest airports to be zero-emission vehicles by 2035. Within the public process for the Advanced Clean Fleet standard, CARB has indicated the policy will require all drayage trucks in the state to be zero-emission vehicles by 2035, aligning with policies already set forth in Southern California (see below).

Legislation passed in 2017 in California (AB 739) already the purchase of zero-emission Class 6-8 vehicles within state operated fleets, beginning at 15 percent of purchases in 2025 and 30 percent of purchases in 2030.

The City of Los Angeles has committed to ensure 100 percent of the city's medium duty trash and recycling trucks are zero emission trucks by 2028 (Garcetti 2019). GreenWaste, the City of Palo Alto's refuse contractor, has also announced plans to run its entire residential fleet on electric vehicles (BYD 2019).

The Mayors of Los Angeles and Long Beach have directed their respective ports to transition the roughly 17,000 drayage trucks serving the ports to 100 percent zero-emission vehicles by 2035. The San Pedro Bay Ports have developed a Clean Air Action plan to support that transition (2017).

The California Public Utilities commission has approved proposals totaling $700 million over 5 years from the three major investor owned utilities in the state to invest in "make ready" infrastructure and charging equipment (CPUC 2018, 2019). Through proposals approved by the CPUC alone, there is funding to supply the charging needs for ***at least*** 18,000 electric trucks and buses on the road.

D) MARKET SIGNALS FOR ELECTRIFICATION

Some of the fleets already making significant commitments to zero emission trucks include:

Amazon. The online retailer recently announced it will deploy 100,000 electric delivery trucks by 2030, with 10,000 being deployed by 2022.

Anheuser-Busch InBev. The company announced orders for 840 battery and fuel cell electric semi trucks as part of its commitment to power 100 percent of its directly operated delivery vehicles with renewable energy by 2025. Anheuser-Busch has also ordered 21 second generation BYD 8TT Class 8 electric trucks.

FedEx. In 2018, FedEx announced it would purchase 100 electric delivery trucks made by Chanje and lease 900 more electric Chanje vehicles through Ryder.

IKEA. In 2018, at California's Global Climate Action Summit, IKEA CEO Jesper Brodin announced a commitment to using EVs for the last-mile portion of all of its product shipments by 2025. The Swedish retailer says it has already electrified all its local delivery vehicles in Shanghai, and plans to do the same in Los Angeles, New York, Paris and Amsterdam by 2020.

PepsiCo. The company announced that it will deploy 15 heavy-duty Tesla battery electric tractors, six Peterbilt 220EV battery electric box trucks, and three BYD 8Y battery electric yard tractors as part of its goal to replace all of its existing diesel-powered freight equipment with zero-and near-zero emission technologies at its Modesto, California site.

UPS. The parcel delivery company recently committed to purchasing 10,000 electric delivery trucks for deployment in the US and Europe. In June 2018, UPS announced intentions to order 1,000 electric delivery vans from Workhorse.

As a sign of the speed at which electrification of vehicles can occur, the city of Shenzhen in China provides an example. A recent report from the Rocky Mountain Institute31 found that from the beginning of 2015 to the end of 2018, Shenzhen's fleet of electric logistics vehicles, vans, and light/medium trucks expanded from 300 to approximately 61,857, representing approximately 35% of the city's overall fleet of urban delivery vehicles.

IV.Overarching goals and timeframe of rule

EPA has identified a number of principles around which it is basing the CTI program. Many of these principles are inconsistent with the principles of the Clean Air Act, as discussed below. We urge EPA to adhere more strictly to the guideposts of the Clean Air Act and its ultimate mission to protect the health and welfare of the American public, rather than sidetrack itself with buzzwords like "'smart' communications and computing technology" or "streamlining…regulatory requirements" which can have the opposite effect.

A. Key goals and principles of the Cleaner Trucks Initiative and the Clean Air Act

EPA has stated that one of its high-level principles is to "give careful consideration to the cost impacts" of any solutions to reduce emissions of NO_x and PM (85 FR 3311). While the Clean Air Act allows for the agency to "consider" cost and energy factors, this is subservient to the primary guiding principle of Section 202(a) of the Clean Air Act, which states that the agency must set "standards which reflect the greatest degree of emission reduction achievable." ***This*** must be the primary goal of the CTI program.

Furthermore, Section 202(a)(3) of the Clean Air Act is quite clear that EPA has the obligation to set "technology-forcing" standards that maximize emissions reductions,[11] yet EPA makes no mention in any of its goals or principles the ways in which this regulation should be a driver for technological progress (85 FR 3307, 3311). It is not enough to "incentivize" innovation (85 FR 3307)—a rulemaking that reflects and upholds the requirements of the Clean Air Act must be ***built*** on innovation and require the deployment of innovative technology solutions.

Finally, while we agree with the agency that a "coordinated 50-state program" is a desirable outcome, upholding this as a principle neglects the role states play in advancing the goals of the Clean Air Act, particularly where it comes to promoting innovative strategies to reduce emissions. We are hopeful that EPA will build its rule upon the strong foundation of state leadership and the advances that state regulations and investments have made both to reduce emissions from heavy-duty vehicles and to transition to zero-emission technologies, but the Clean Air Act does not give EPA the authority to overrule the implementation of those programs and sacrifice critical local needs simply for 50-state coordination. Particularly where the federal government has neglected to uphold its responsibility to set the greatest degree of emission reduction achievable, it is desirable and necessary for states to step up and protect their residents with stronger standards, as allowed for under the Clean Air Act (Sections 177 and 209).

B. Rulemaking timeline

The Agency has underscored as a guiding principle "careful consideration of costs", yet it acknowledges that it may move forward with an NPRM even if a planned teardown study is still underway (85 FR 3312)—such action seems at odd with the stated guideline. Teardown studies have long been established

---

[11] "Case and statutory law support the broad authority of EPA to force substantial change on the status quo on an industry-wide basis. The 'technology-forcing goals' of Subchapter II, the portion of the Clean Air Act that establishes emissions standards for moving vehicles, are well recognized. See, e.g., ***Whitman v. American Trucking Ass'ns***, 531 U.S. 457, 491-492, 121 S. Ct. 903, 149 L. Ed. 2d 1 (2001) (Breyer, J. dissenting). The technology-forcing authority of the Clean Air Act is embodied in the language of the Act that directs EPA to promulgate standards "that reflect the greatest degree of emission reduction achievable through the application of technology which the Administrator determines will be available for the model year to which the standards apply,. . . ." 42 U.S.C. § 7521(a)(3)(A) (i). EPA is thus empowered to set standards for future model years based on reasonable projections of technology that may not be available currently. ***NRDC v. Thomas***, 805 F.2d 410, 429 (D.C.Cir.1986)." –***Cent. Valley Chrysler-Jeep, Inc. v. Goldstene***, 529 F. Supp. 2d 1151, 1178 (E.D. Cal. 2007).

as the “most reliable cost estimating methodology” (NRC 2015)—the agency has not justified why it should move forward with a rulemaking given this outstanding data.

Similarly, the agency has planned to address “longer periods of mandatory emissions-related component warranties” (85 FR 3307), yet it acknowledges that a program designed to validate a protocol for deterioration testing over extended warranty and useful-life periods will not be completed until after the agency plans to issue an NPRM (85 FR 3329). This, too, is unacceptable. In both of these instances, the agency is proposing to move forward with a proposal without the completion of research which is foundational to any proposed approach, and for which the agency is suggesting an exclusion of the public’s opportunity for comment and review.

Because the agency intends to align implementation of the CTI program with model year 2027 (85 FR 3311), the agency is under no time constraint that could justify the exclusion of critical research—it has already set the timeline for implementation of the rule, and the 4-year lead-time requirement gives the agency a nearly 3-year window to finalize a rule. This is more than enough time to complete their research and offer appropriate time for public comment and review without rushing forward prematurely, as the agency currently intends.

The Union of Concerned Scientists emphasizes that public policy must be based on best available data, using technical analysis to support innovative, practical solutions to the planet’s most pressing problems. EPA should have no less rigorous a standard (within its statutory authority).

V. Summary

Heavy-duty trucks are expected to remain a key contributor to mobile source NO_x and $PM_{2.5}$ emissions. State leadership will help drive emissions control improvements over the next few years, but a strong 50-state rule for 2027 that builds upon these developments will be critical to reducing these harmful emissions nationwide, particularly along freight corridors and urban areas. Communities of color are disproportionately impacted by transportation-related emissions, and those most affected by truck pollution stand to benefit significantly from a strong, nationwide rule.

The CTI program is an opportunity for this administration to uphold the requirements of the Clean Air Act while working with CARB and building upon the state leadership currently advancing the industry. Reshaping the heavy-duty engine and vehicle test procedures can ensure that the country is no longer leaving emissions reductions on the table:

- **FTP target:** Analysis of the latest scientific and technical information shows that a 0.02 g/bhp-hr FTP standard is achievable by 2027 through a number of different approaches, building upon advances in aftertreatment systems but also incorporating more advanced engine controls which can improve fuel economy while simultaneously reducing NO_x.
- **Low-load cycle:** Driven by the inclusion of a low-load cycle, these technologies can help mitigate emissions in areas like ports and freight hubs that see a disproportionate share of cold-start emissions.
- **Warranty/Useful life:** Increasing the warranty and useful-life periods of these technologies will ensure that they continue to remain effective throughout the most likely vehicle lifetime.
- **$PM_{2.5}$ standard:** DPFs have driven emissions reductions to levels that far exceed the current requirements, so a reduced $PM_{2.5}$ standard is necessary to ensure that manufacturers do not backslide on this progress.

- **In-use testing:** Replacing the NTE process with a MAW approach would better ensure that these test procedures result in real-world reductions, and allow for better monitoring and enforcement of tampering and malmaintenance of emissions equipment.
- **Glider trucks:** Requiring that engines used in glider trucks meet the 2010 emissions test or better would guarantee that all new vehicles are required to control emissions and eliminate the worst-polluting engines from the fleet instead of granting them new life under the current, weak cap.

Because of the progress in electrifying trucks to date, driven by state investment and state requirements, it is possible that the CTI program could be the last significant soot and smog regulation on heavy-duty vehicles. The CTI program should therefore reflect and accelerate the progress in zero-emission vehicles, so that we cannot just minimize tailpipe pollution from heavy-duty trucking, but instead eliminate it entirely.

VI. References

All references accessed February 20, 2020.

Abuelsamid, S. 2019. "Garrett electric turbochargers headed to production in 2021." ***Forbes***, October 17, 2019. Online at ***https://www.forbes.com/sites/samabuelsamid/2019/10/17/garrett-electric-turbochargers-headed-to-production-in-2021/.***

Badshah, H., F. Posada, and R. Muncrief. 2019. Current state of NOx emissions from in-use heavy-duty diesel vehicles in the United States. Whitepaper of the International Council on Clean Transportation (ICCT). November 26, 2019. Online at ***https://theicct.org/publications/nox-emissions-us-hdv-diesel-vehicles.***

Boriboonsomsin,K., T. Durbin, G. Scora, K. Johnson, D. Sandez, A. Vu, Y. Jiang, A. Burnette, S. Yoon, J. Collins, Z. Dai, C. Fulper, S. Kishan, M. Sabisch, and D. Jackson. 2018. "Real-world exhaust temperature profiles of on-road heavy-duty vehicles equipped with selective catalytic reduction." ***Sci. Total Environ.*** **634**, 909-921. Online at ***http://dx.doi.org/10.1016/j.scitotenv.2018.03.362.***

Bruck, R., M. Presti, O. Holz, A. Geisselmann, and A. Scheuer, A. 2018. The Way to Achieve "CARB post 2023" Emission Legislation for Commercial Vehicles. (Presentation). The 39th International Vienna Motor Symposium 26th - 27th April 2018. Vienna.

BYD. 2019. "Public-private partnership to electrify waste expo." Press release, May 1, 2019. Online at ***https://en.byd.com/news-posts/press-release-public-private-partnership-to-electrify-waste-expo/.***

BYD. 2020. "BYD delivers 100th battery-electric truck in the United States." Press release, January 8, 2020. Online at ***https://en.byd.com/news-posts/byd-delivers-100th-battery-electric-truck-in-the-united-states/.***

CARB (California Air Resources Board). 2017. Proposed heavy-duty vehicle (HDV) warranty period amendments. (Presentation). Heavy-duty low NOx rulemaking workshop, Diamond Bar, CA, July 12, 2017. Online at ***https://ww3.arb.ca.gov/msprog/hdlownox/files/workshop071217/warrantyws_presentation.pdf.***

CARB. 2019a. Heavy-duty low NOx program: Proposed heavy-duty engine standards. (Presentation). Heavy-duty low NOx rulemaking workshop, Diamond Bar, CA, September 26, 2019. Online at

https://ww3.arb.ca.gov/msprog/hdlownox/files/workgroup_20190926/staff/01_hde_standards.pdf.

CARB. 2019b. Heavy-duty low NOx program: Low load cycle. (Presentation). Heavy-duty low NOx rulemaking workshop, Diamond Bar, CA, September 26, 2019. Online at ***https://ww3.arb.ca.gov/msprog/hdlownox/files/workgroup_20190926/staff/03_llc.pdf.***

CARB. 2019c. Heavy-duty low NOx program: Proposed heavy-duty useful life and step 2 warranty amendments. (Presentation). Heavy-duty low NOx rulemaking workshop, Diamond Bar, CA, September 26, 2019. Online at ***https://ww3.arb.ca.gov/msprog/hdlownox/files/workgroup_20190926/staff/04_hd_ul_step_2_warranty.pdf.***

CARB. 2019d. Low load cycle development. (Presentation). Heavy-duty low NOx rulemaking workshop, Sacramento, CA, January 23, 2019. Online at ***https://ww3.arb.ca.gov/msprog/hdlownox/files/workgroup_20190123/02-llc_ws01232019-1.pdf.***

CARB. 2019e. California Air Resources Board staff current assessment of the technical feasibility of lower NOx standards and associated test procedures for 2022 and subsequent model year medium-duty and heavy-duty diesel engines. Prepared April 18, 2019. Online at ***https://ww3.arb.ca.gov/msprog/hdlownox/white_paper_04182019a.pdf.***

CARB. 2019f. Advanced Clean Trucks: Total cost of ownership discussion document. Sacramento, CA. Online at ***http://ww2.arb.ca.gov/sites/default/files/2019-02/190225tco_0.pdf.***

CARB. 2019g. Proposed Advanced Clean Trucks Regulation. (Presentation). Sacramento, CA, December 12, 2019. Online at ***https://ww3.arb.ca.gov/board/books/2019/121219/pres19-12-4.pdf.***

CARB. 2020a. Heavy-Duty Engines and Vehicles, including Urban Buses, and Engines Used in Diesel or Incomplete Medium-Duty Vehicles of 8,501-14,000 Pound GVWR Executive Orders – 2020. Online at ***https://ww3.arb.ca.gov/msprog/onroad/cert/mdehdehdv/2020/2020.php.***

CARB. 2020b. Advanced clean truck fleets. (Presentation). Zero-emission fleet rule workshop, Diamond Bar, CA, February 12, 2020. Online at ***https://ww2.arb.ca.gov/sites/default/files/2020-02/200212presentation_ADA_1.pdf.***

Chen, D. 2008. California's heavy-duty vehicle idling regulations. (Presentation). NCSL conference call, January 28, 2008. Online at ***https://www.ncsl.org/print/energy/dchenidling07.pdf.***

Clyne, J. 2019. Heavy duty omnibus low NOx rulemaking workshop. (Presentation). Heavy-duty low NOx rulemaking workshop, Diamond Bar, CA, September 26, 2019. Online at ***https://ww3.arb.ca.gov/msprog/hdlownox/files/workgroup_20190926/guest/04_nysdec_hdnox.pdf.***

Cooke, D.W. 2015. Comments concerning greenhouse gas emissions standards and fuel efficiency standards for medium- and heavy-duty engines and vehicles (Phase 2). EPA-HQ-OAR-2014-0827-1329. Online at ***https://www.regulations.gov/document?D=EPA-HQ-OAR-2014-0827-1329.***

Cooper, C. 2019. The Northeast's need for NOx reductions. (Presentation). Heavy-duty low NOx rulemaking workshop, Diamond Bar, CA, September 26, 2019. Online at ***https://ww3.arb.ca.gov/msprog/hdlownox/files/workgroup_20190926/guest/02_nescaum_presentation_carb_workshop.pdf.***

CPUC (California Public Utilities Commission). 2018. Summary of Decision on Transportation Electrification Program Proposals from the Investor-Owned Utilities, May 31, 2018.

CPUC. 2019. Proposed decision of Aljs Hymes and Goldberg. Online at ***http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M311/K114/311114709.pdf.***

Cullen, D. 2019. “Volvo to sell electric Class 8 truck in the U.S. by end of 2020.” ***Heavy-Duty Trucking Info***, October 7, 2019. Online at ***https://www.truckinginfo.com/341895/volvo-to-start-selling-electric-class-8-truck-here-at-end-of-2020.***

Decker, D. 2019. Mobile sources and air quality in Colorado. (Presentation). Heavy-duty low NOx rulemaking workshop, Diamond Bar, CA, September 26, 2019. Online at ***https://ww3.arb.ca.gov/msprog/hdlownox/files/workgroup_20190926/guest/05_colorado_mss_for_carb.pdf.***

Di Filippo, J., C. Callahan, and N. Golestani. 2019. Zero-emission drayage trucks: Challenges and opportunities for the San Pedro Bay ports. UCLA Luskin Center for Innovation, October 2019. Online at ***https://innovation.luskin.ucla.edu/wp-content/uploads/2019/10/Zero_Emission_Drayage_Trucks.pdf.***

Dorobantu, M. 2019. Commercial Vehicle Powertrains in the Era of Simultaneous NOx and CO2 Reduction. (Presentation). 16th SAE Brasil forum on diesel and alternative technologies for commercial and off-road vehicles, September 4, 2019.

Eaton. 2020. “TVS applications: Diesel engine EGR pump.” Product description. Online at ***https://www.eaton.com/us/en-us/products/engine-solutions/superchargers/TVS-technology-applications/tvs-diesel-egr-pump.html.***

EPA (Environmental Protection Agency). 2015. Exhaust emission rates for heavy-duty on-road vehicles in MOVES2014. EPA-420-R-15-015a. Online at ***https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100NO46.pdf.***

EPA. 2016. Integrated Science Assessment (ISA) for oxides of nitrogen – Health criteria (Final report, 2016). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-15/068. Online at ***https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=310879.***

EPA. 2019a. Integrated Science Assessment (ISA) for particulate matter (Final report, 2019). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-19/188. Online at ***https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=347534.***

EPA. 2019b. Integrated Science Assessment (ISA) for ozone and related photochemical oxidants (External review draft). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-19/093. Online at ***https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=344670.***

EPA. 2020. Heavy-duty highway gasoline and diesel certification data (Model years: 2015-present). Online at ***https://www.epa.gov/sites/production/files/2020-01/heavy-duty-gas-and-diesel-engines-2015-present.xlsx.***

Farrell, P. 2019. Connecticut’s air quality challenges. (Presentation). Heavy-duty low NOx rulemaking workshop, Diamond Bar, CA, September 26, 2019. Online at ***https://ww3.arb.ca.gov/msprog/hdlownox/files/workgroup_20190926/guest/03_ctdeep_scaqmd_presentation.pdf.***

Feeley, E. 2019. Recent Oregon legislative action on medium and heavy duty diesel. (Presentation). Heavy-duty low NOx rulemaking workshop, Diamond Bar, CA, September 26, 2019. Online at ***https://ww3.arb.ca.gov/msprog/hdlownox/files/workgroup_20190926/guest/06_oregon_legislative_action_on_md_and_hd_diesel.pdf.***

Flint, S.E. and E.C. White. 2019. Letter to Jack Kitowski, Division Chief, Mobile Source Control Division, California Air Resources Board, September 24, 2019, on behalf of the National Association of Clean Air Agencies (NACAA). Online at ***https://ww3.arb.ca.gov/msprog/hdlownox/files/workgroup_20190926/guest/07_nacca_letter_to_carb_workshop.pdf.***

FTA (Federal Transit Administration). 2020. "Low or no emission vehicle program – 5339(c)." Online at ***https://www.transit.dot.gov/funding/grants/lowno.***

Garcetti, E. 2019. L.A.'s green new deal: Sustainable City pLAn. Online at ***https://plan.lamayor.org/sites/default/files/pLAn_2019_final.pdf.***

Garcia, E., V. Triantopoulos, A. Boehman, A., M. Taylor, and J. Li. 2020. "Impact of Miller Cycle Strategies on Combustion Characteristics, Emissions and Efficiency in Heavy-Duty Diesel Engines." ***SAE Technical Paper*** 2020-01-1127. Online at ***https://saemobilus.sae.org/content/2020-01-1127/.***

Giechaskiel, B., A. Joshi, L. Ntziachristos, and P. Dilara. 2019. "European regulatory framework and particulate matter emissions of gasoline light-duty vehicles: A review." ***Catalysts*** **9**, 586. Online at ***http://dx.doi.org/10.3390/catal9070586.***

Girard, J., G. Cavataio, R. Snow, and C. Lambert. "Combined Fe-Cu SCR systems with optimized ammonia to NOx ratio for diesel NOx control." ***SAE Int. J. Fuels Lubr.*** **1** (1), 603-610. Online at ***https://doi.org/10.4271/2008-01-1185.***

Hall, D., and N. Lutsey. 2019. Estimating the infrastructure needs and costs for the launch of zero-emission trucks. Washington, DC: The International Council on Clean Transportation. Online at ***https://theicct.org/sites/default/files/publications/ICCT_EV_HDVs_Infrastructure_20190809.pdf.***

Han, J., G. Sandhu, D. Sonntag, and D. Bizer-Cox. 2019. Planned updates to EPA's MOVES emission model for heavy-duty onroad vehicles. (Presentation). 2019 International Emissions Inventory Conference, Dallas, TX, July 31, 2019. Online at ***https://www.epa.gov/sites/production/files/2019-08/documents/915am_han_508_0.pdf.***

Hirsch, J. 2019. "Daimler puts first eCascadia electric trucks in service." ***Trucks.com***, August 21, 2019. Online at ***https://www.trucks.com/2019/08/21/daimler-puts-first-ecascadia-electric-trucks-in-service/.***

Honardar, S., H. Busch, T. Schnorbus, C. Severin, A.F. Kolbeck, and T. Korfer. 2011. "Exhaust temperature management for diesel engines assessment of engine concepts and calibration strategies with regard to fuel penalty." ***SAE Technical Paper*** 2011-24-0176. Online at ***https://doi.org/10.4271/2011-24-0176.***

ICF. No date b. Comparison of medium- and heavy-duty technologies in California: Scenario analysis. San Jose, CA. In press.

Kamasamudram, K., N. Currier, T. Szailer, and A. Yezerets. 2010. "Why Cu- and Fe-zeolite SCR catalysts behave differently at low temperatures." ***SAE Int. J. Fuels Lubr.*** **3** (1), 664-672. Online at ***https://doi.org/10.4271/2010-01-1182.***

Kasab, J. M. de Monte, K. Hadl, H. Noll, S. Mannsberger, G. Graf, H. Theissl, and A. Arnberger. Using close-coupled SCR to meet ultra-low NOx requirements. (Presentation). 2019 CLEERS

Workshop, Ann Arbor, MI, September 17-19, 2019. Online at ***https://cleers.org/wp-content/uploads/formidable/3/2019CLEERS_Kasab_Web.pdf.***

Kerschner, B., and D. Barker. 2017. Survey and analysis of heavy-duty vehicle warranties in California (15MSC009). Prepared by the Institute for Social Research for the California Air Resources Board, December 2017. Online at ***https://ww3.arb.ca.gov/regact/2018/hdwarranty18/apph.pdf.***

Matsui, H., D.S. Hamilton, and N.M. Mahowald. 2018. "Black carbon radiative effects highly sensitive to emitted particle size when resolving mixing-state diversity." ***Nature Communications*** **9**, 3446. Online at ***https://www.nature.com/articles/s41467-018-05635-1.***

McCarthy, J. 2019a. Meeting Future Low Load Emissions Using Cylinder Deactivation and EGR Pumps to Achieve Simultaneous NOx and CO2 Reduction. (Presentation). Emissions 2019 Conference, Livonia, MI, June 5, 2019.

McCarthy, J. 2019b. Simultaneous CO2 and NOx Reduction for Medium & Heavy- Duty Diesel Engines Using Cylinder Deactivation. (Presentation). 16^{th} SAE Brasil forum on diesel and alternative technologies for commercial and off-road vehicles, September 4, 2019.

MECA (Manufacturers of Emission Controls Association). 2013. Ultrafine particulate matter and the benefits of reducing particle numbers in the United States. July 2013. Online at ***http://www.meca.org/resources/MECA_UFP_Report_0713_Final.pdf.***

MECA. 2019. Technology feasibility for model year 2024 heavy-duty diesel vehicles in meeting lower NOx standards. June 2019. Online at ***http://www.meca.org/resources/MECA_MY_2024_HD_Low_NOx_Report_061019.pdf.***

MECA. 2020. Technology feasibility for heavy-duty diesel trucks in achieving 90 percent lower NOx standards in 2027. February 2020. Online at ***http://www.meca.org/resources/MECA_2027_Low_NOx_White_Paper_FINAL.pdf.***

Mohai, P., D. Pellow, and J.T. Roberts. 2009. "Environmental justice." ***Ann. Rev. Env. Resources*** **34**, 403-430. Online at ***https://www.annualreviews.org/doi/pdf/10.1146/annurev-environ-082508-094348.***

Neely, G., C. Sharp, M.S. Pieczko, and J.E. McCarthy. 2019. Simultaneous NOx and CO2 Reduction Using Diesel CDA With NVH Setup Strategy on a Heavy-Duty Diesel Engine in a Dyno Test Cell Showing Means to Meet CARB Low NOx in Steady State, Transient and Low Load Cycle.

NESCAUM (Northeast States for Coordinated Air Use Management). 2019. "Multi-state medium- and heavy-duty zero emission vehicle initiative." Statement of intent, December 12, 2019.

NRC (National Research Council). 2015. Cost, Effectiveness, and Deployment of Fuel Economy Technologies for Light-Duty Vehicles. Washington, DC: The National Academies Press. Online at ***https://doi.org/10.17226/21744***.

NRC. 2019. Reducing Fuel Consumption and Greenhouse Gas Emissions of Medium- and Heavy-Duty Vehicles, Phase Two: Final Report. Washington, DC: The National Academies Press. Online at ***https://doi.org/10.17226/25542.***

O'Dea, J. 2019. Ready for Work: Now is the time for heavy-duty electric vehicles. December 11, 2019. Online at ***https://www.ucsusa.org/resources/ready-work.***

Ohlwein, S., R. Kappeler, J.M. Kutlar, N. Künzil, and B. Hoffmann. "Health effects of ultrafine particles: a systematic literature review update of epidemiological evidence." ***Int. J. Public Health*** **64** (4), 547-559. Online at ***http://dx.doi.org/10.1007/s00038-019-01202-7***.

Park, J. 2019. "Eaton looks to advanced engine technology to combat emissions." ***Heavy-Duty Trucking Info***, April 8, 2019. Online at ***https://www.truckinginfo.com/329084/eaton-looks-to-advanced-engine-technology-to-combat-emissions.***

Phadke, A., A. Khandekar, M. McCall, N. Karali, and D. Rajagopal. 2019. Long-haul battery electric trucks are technically feasible and economically compelling. Berkeley, CA: Lawrence Berkeley National Laboratory. Online at ***http://eta-publications.lbl.gov/sites/default/files/working_paper_005_battery_electric_trucks_906_0.pdf***.

Pratt, G.C., M.L. Vadali, D.L. Kvale, and K.M. Ellickson. 2015. "Traffic, air pollution, minority and socio-economic status: Addressing inequities in exposure and risk." ***Int. J. Environ. Res. Public Health*** **12** (5), 5355-5372. Online at ***http://dx.doi.org/10.3390/ijerph120505355.***

Reed, G., A. Desikan, and C. Kalman. 2020. Endangering generations: How the Trump administration's assault on science is harming children's health. Online at ***https://www.ucsusa.org/resources/endangering-generations.***

Roberts, L., M. Magee, G. Shaver, A. Garg, J. McCarthy, E. Koeberlein, E. Holloway, R. Shute, D. Koeberlein, and D. Nielsen. 2015. "Modeling the impact of early exhaust valve opening on exhaust aftertreatment thermal management and efficiency for compression ignition engines." ***Int. J. Eng. Res.*** **16** (6), 773-794. Online at ***https://doi.org/10.1177%2F1468087414551616.***

Rodriguez, F., and F. Posada. 2019. Future heavy-duty emission standards: An opportunity for international harmonization. White paper of the International Council on Clean Transportation (ICCT). November 2019. Online at ***https://theicct.org/sites/default/files/publications/Future%20_HDV_standards_opportunity_20191125.pdf.***

Salehi, R., and A.G. Stefanopoulou. 2018. "Optimal exhaust valve opening control for fast aftertreatment warm up in diesel engines." ***Proceedings of ASME 2018 Dynamic Systems and Control Conference, Vol. 2***. DSCC2018-9178, V002T26A003. Online at ***https://doi.org/10.1115/DSCC2018-9178.***

Sandhu, G.S., and D. Sontag. 2016. Update to running exhaust criteria pollutant emission rates for model year 2010+ heavy-duty diesel vehicles. (Presentation). FACA MOVES Review Work Group, Ann Arbor, MI, December 7, 2016. Online at ***https://www.epa.gov/sites/production/files/2017-01/documents/running-exhaust-cri-pollutant-emission-rates-my-2010-hd-vehicles.pdf.***

San Pedro Bay Ports. 2017. Clean Air Action Plan 2017: Final. November 2017. Online at ***https://cleanairactionplan.org/documents/final-2017-clean-air-action-plan-update.pdf/.***

SCAQMD (South Coast Air Quality Management District), Pima County Dept. of Environmental Quality (Arizona), Bay Area Air Quality Management District (California), Connecticut Dept. of Energy and Environmental Protection, Delaware Dept. of Natural Resources and Environmental Control, Division of Air Quality Washoe Co. Health District, Air Quality Management (Nevada), New Hampshire Dept. of Environmental Services, New York City Dept. of Environmental Protection (New York), Akron Regional Air Quality Management District (Ohio), Washington State Dept. of Ecology, and Puget Sound Clean Air Agency (Washington). 2016. Petition to Administrator Gina McCarthy, EPA, for rulemaking to adopt ultra-low NOx exhaust emission standards for on-road heavy-duty trucks and engines, June 3, 2016. Online at

https://www.epa.gov/sites/production/files/2016-09/documents/petition_to_epa_ultra_low_nox_hd_trucks_and_engines.pdf.

Sharp, C. 2019. Update on Heavy-duty low NO_x demonstration programs at SwRI. (Presentation). Heavy-duty low NOx rulemaking workshop, Diamond Bar, CA, September 26, 2019. Online at ***https://ww3.arb.ca.gov/msprog/hdlownox/files/workgroup_20190926/guest/swri_hd_low_nox_demo_programs.pdf.***

Sharp, C., C. Webb, S. Yoon, M. Carter, and C. Henry. 2017. "Achieving Ultra Low NOX Emissions Levels with a 2017 Heavy-Duty On-Highway TC Diesel Engine - Comparison of Advanced Technology Approaches." ***SAE Int. J. Engines*** 10 (4), 1722-1735. Online at ***https://doi.org/10.4271/2017-01-0956.***

Tarnutzer, S.A. 2017. New and Emerging Energy Conversion Opportunities. (Presentation). SAE Commercial Vehicle Engineering Conference, Chicago, Sept. 2017.

Tessum, C.W., J.D. Hill, and J.D. Marshall. 2017. "InMAP: A model for air pollution interventions." ***PLoS ONE*** 12 (4), e0176131. Online at ***https://doi.org/10.1371/journal.pone.0176131.***

Van Cleve, S. 2019. Letter to Mary Nichols and CARB re: Support for a strengthened Advanced Clean Truck rule, December 9, 2019. Online at ***https://www.arb.ca.gov/lists/com-attach/120-act2019-VyMFZlAiWWYEYwdY.pdf.***

VW (Volkswagen). 2019. "Innovative twin dosing reduces NOx emissions by approx. 80 percent." Press release, August 29, 2019. Online at ***https://www.volkswagen-newsroom.com/en/press-releases/innovative-twin-dosing-reduces-nox-emissions-by-approx-80-percent-5281.***

Yoon, S., J.F. Collins, C. Misra, J.D. Herner, M.W. Carter, and T.P. Sax. 2017. "In-use emissions from 2010-technology heavy-duty trucks: Impacts on air quality planning in California." ***TRR: J. of the Transp. Res. Board*** 2627 (1), 1-8. Online at ***https://doi.org/10.3141%2F2627-01.***

Zhang, C., E.S. Miller, A.J. Kotz, K.J. Kelly, and M.J. Thornton. 2019. Characterization of Medium- and Heavy-Duty Vehicle Operations from In-Use Data: An Analysis of Starts, Soak Time, and Warm-Up Duration. United States. Online at ***http://www.dx.doi.org/10.2172/1575198.***

Ready for Work

Now Is the Time for Heavy-Duty Electric Vehicles

HIGHLIGHTS

Electric trucks and buses represent the next frontier for electric vehicles. Increasingly available, they have zero tailpipe emissions and lower life cycle global warming emissions compared with other types of trucks or buses. Widespread electrification already makes sense for several classes of heavy-duty vehicles based on their operating characteristics, the range of today's battery technologies, and similar if not cheaper ownership costs. While internal combustion engines have been in use for more than a century, three types of policies can accelerate the electrification of trucks and buses: financial incentives, investments in charging infrastructure, and standards that increase the manufacture and purchase of heavy-duty electric vehicles. All of these policies should center on improving air quality in communities most burdened by vehicle pollution.

Light-duty electric vehicles in the United States hit a major milestone at the end of 2018: total sales-to-date passed the 1 million mark (Auto Alliance n.d.). While significant uptake of electric passenger vehicles is still needed to reduce the climate and air quality impacts of the light-duty vehicle sector, signals in policy, technology, and the market suggest that widespread electrification of cars, SUVs, and light pickup trucks is possible.

What about electrifying the other vehicles on the road, heavy-duty vehicles? While further from reaching 1 million sales, trucks and buses are undoubtedly the next frontier for widespread electrification of vehicles.

Today's heavy-duty vehicles, fueled predominately with diesel, have a big impact on air quality, public health, and the climate. But electric trucks and buses have zero tailpipe emissions, and, powered by today's electricity grid, produce fewer global warming emissions than their combustion counterparts. Increasing availability and decreasing costs point to a bright future for heavy-duty electric vehicles. Policy support will be critical, however, to transition from the ubiquity of internal combustion engines.

Jimmy O'Dea/UCS

Semi trucks that transport cargo containers to and from ports and railyards ("drayage trucks") often travel short distances per trip and are well-suited for electrification. Several electric models, with ranges up to 300 miles, are already in demonstration today.

Union of Concerned Scientists

Why Trucks and Buses?

Nationally, the transportation sector represents the largest source of global warming emissions—29 percent of all emissions (EPA 2019).[1] It is also a major source of air pollution in the United States. Within the transportation sector, heavy-duty vehicles disproportionately contribute to emissions.

Despite comprising just 10 percent of vehicles on US roads, heavy-duty vehicles contribute 28 percent of global warming emissions from the nation's on-road transportation sector (EIA 2016; FHWA 2016; EPA 2019) (see Box 1).[2] They are also responsible for 45 percent of on-road NO_x emissions (oxides of nitrogen) (see Figure 1) and 57 percent of on-road, direct $PM_{2.5}$ emissions (particulate matter less than 2.5 micrometers in diameter) (EPA 2018a).[3] NO_x—a precursor to smog and $PM_{2.5}$—and particulate matter are major sources of air pollution, and they pose significant health risks at all stages of life, from premature births to premature deaths (Caiazzo et al. 2013; Darrow et al. 2009). Heart attacks, cancer, reduced lung function, and exacerbation of asthma are the health effects most frequently associated with air pollution from vehicles, but researchers have reported negative health outcomes for many other parts of the body as well (ALA 2019).

On-road sources of air pollution disproportionately burden communities of color and low-income communities due to their proximity to roads and vehicular traffic. Asian Americans, African Americans, and Latinos are exposed to 34 percent, 24 percent, and 23 percent more $PM_{2.5}$ pollution (respectively) from cars, trucks, and buses than the national average (Reichmuth 2019a; Reichmuth 2019b).

The disproportionate contribution of heavy-duty vehicles to global warming emissions results from both the large amount of fuel consumed per mile and the high mileage they travel compared with light-duty vehicles. In 2017, diesel transit buses averaged 4.0 miles per gallon (mpg); tractor (semi) trucks, 6.0 mpg; and single-unit trucks (i.e., non-semi trucks), 7.4 mpg; while cars averaged 24.2 mpg (FHWA 2019; FTA 2018). Additionally, the average semi truck travels more than 60,000 miles per year (with newer trucks traveling close to 90,000 miles per year), compared with less than 12,000 miles for the average passenger car (FHWA 2019; Komanduri 2019).

The prevalence of diesel engines in heavy-duty vehicles also contributes to their large share of NO_x and $PM_{2.5}$ emissions compared with light-duty vehicles, which predominantly use gasoline engines (see Box 2, p. 4). More than 50 percent of

[Despite comprising just 10 percent of vehicles on US roads, heavy-duty vehicles contribute 45 percent of NO_x emissions from the nation's on-road transportation sector.]

BOX 1.

What Is a Heavy-Duty Vehicle? 2b or Not 2b?

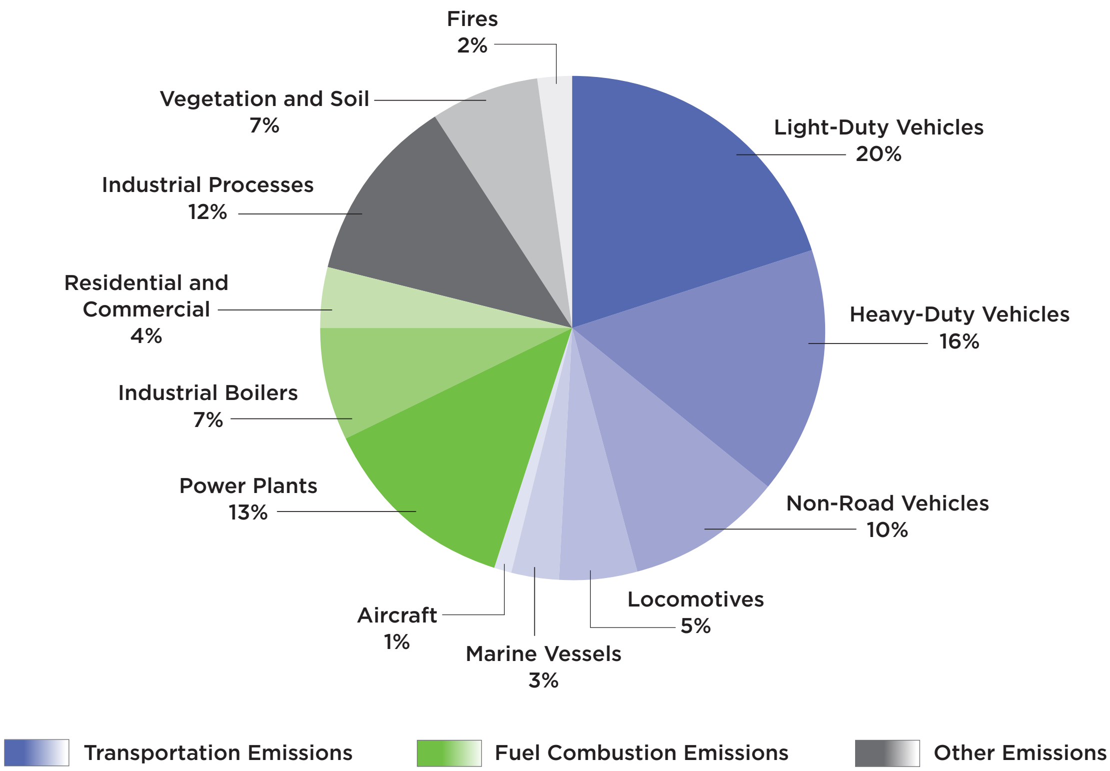
Ask three people, three databases, or three government agencies to define a heavy-duty vehicle and you will get three different answers (AFDC n.d.). Vehicles are categorized into "classes" based on their gross vehicle weight rating (GVWR), ranging from Class 1 (cars and most SUVs) to Class 8 (semi trucks and transit buses). GVWR is the maximum weight at which a fully loaded vehicle is rated to operate, including cargo, passengers, etc.

Definitions of heavy-duty vehicles vary on which classes they include, especially whether or not they include Class 2b vehicles (GWVR of 8,501 to 10,000 pounds). Given the large number of Class 2b vehicles compared with other heavy-duty vehicles (roughly 50 percent or more of all Class 2b–8 vehicles), it is important to recognize whether data include this class or not (Birky et al. 2017). Heavy-duty vehicle statistics cited in this report include Class 2b vehicles.

Vehicles in the Class 2b category cover a range of commercial and personal applications, including cargo vans (e.g., Mercedes-Benz Sprinter) and pickup trucks (e.g., Ford F-250). Unlike Class 3–8 vehicles, roughly three-quarters of which use diesel, Class 2b vehicles more commonly have gasoline engines than diesel (roughly two-thirds are gasoline) (CARB 2018a; Davis et al. 2017; Birky et al. 2017). In light-duty vehicles, diesel comprises less than 1 percent of the population (EIA 2019b).

Note, GVWR is different than a vehicle's "curb weight"—the weight of the vehicle without a load—and "gross vehicle weight"—the actual weight of the vehicle and load during operation (40 US Code). In general, a person must have a commercial driver's license to operate a vehicle with GVWR over 26,000 pounds or for transporting hazardous materials or 15 or more passengers (FMCSA 2017). GVWR also does not include the weight of a trailer. For that, there is "gross vehicle *combined* rating."

FIGURE 1. National Emissions of Nitrogen Oxides, by Sector



In the United States, heavy-duty vehicles are the second largest source of nitrogen oxides, a major air pollutant.

SOURCE: EPA 2018A.

Jimmy O'Dea/UCS

Delivery trucks are ideal candidates for electrification, given their local routes and operating ranges. Most delivery trucks travel less than 100 miles per day, well within the range of electric models on the market today.

BOX 2.

Why Diesel Engines Emit More Pollutants

A gasoline engine compresses a mixture of fuel and air and ignites it with the help of a spark. A diesel engine compresses air to higher pressures, increasing its temperature enough to ignite the diesel when it subsequently enters the engine's cylinder. The long crankshaft used to compress air in a diesel engine produces a higher torque than gasoline engines, which makes diesel the preferred fuel over gasoline for vehicles carrying heavy loads. However, the higher operating temperature of diesel engines favors the formation of NO_x compared with gasoline engines. Higher emissions of particulate matter from diesel engines result from higher levels of incomplete fuel combustion. The same advantages that diesel offers over gasoline—higher torque and better efficiency—are features that electric motors offer over diesel (Chandler, Espino, and O'Dea 2016).

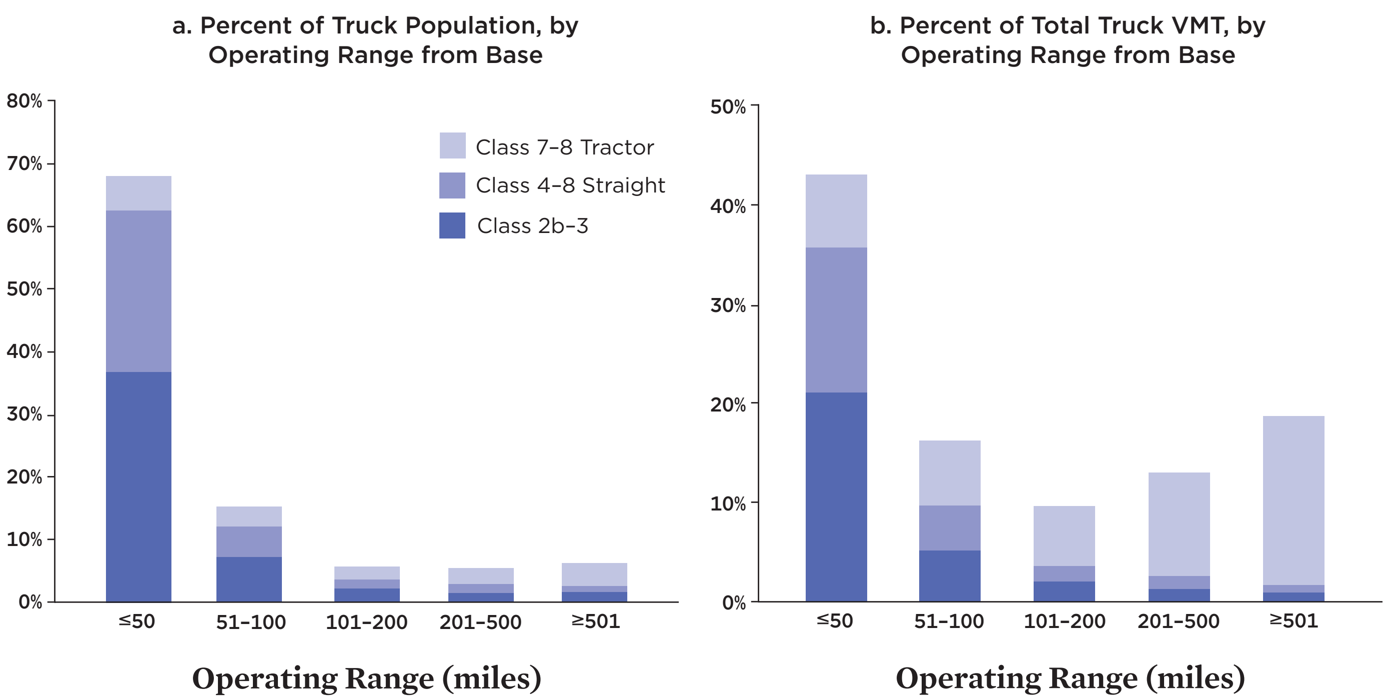
heavy-duty vehicles (Classes 2b–8) have diesel engines, compared with less than 1 percent of light-duty vehicles. In the heaviest of vehicle classes (e.g., semi trucks), nearly every vehicle is diesel-powered (Komanduri 2019).

ELECTRIFICATION CAN MEET MOST VEHICLES' NEEDS

A common question about electric vehicles is whether their range can meet the needs of a given application. The answer is yes; today's battery technology is suitable for many uses of trucks and buses.

Heavy-duty vehicles often travel to predictable destinations with consistent mileage, making them good candidates for electrification. Many trucks and buses operate over short urban routes and stop frequently (USCB 2004). Nationally, more than 80 percent of all heavy-duty trucks (Class 2b and above) have a primary operating range (the farthest distance from the vehicle's home base) of less than 100 miles; nearly 70 percent have an operating range of less than 50 miles (Figure 2).[4]

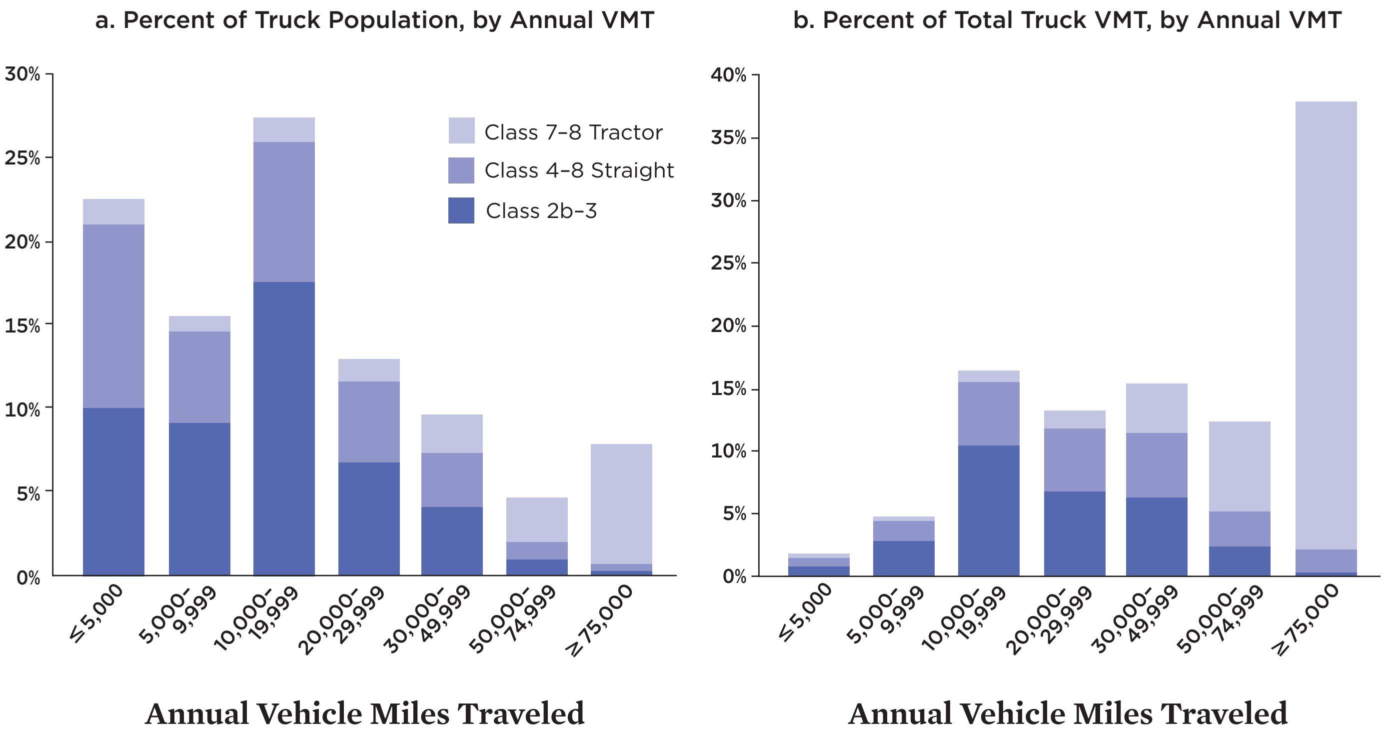
FIGURE 2. Operating Range of Heavy-Duty Trucks



Many heavy-duty trucks operate within 100-mile ranges (left), and many vehicle miles traveled (VMT) are attributable to trucks with operating ranges less than 100 miles (right). These trucks are particularly well-suited to early electrification efforts.

SOURCE: USCB 2004.

FIGURE 3. Annual Mileage of Heavy-Duty Trucks



Many trucks have annual mileages that suggest compatibility with today's battery and fuel cell technologies (left), although a small fraction of vehicles account for the bulk of the total miles traveled by trucks (right).

SOURCE: USCB 2004.

Data on annual mileage further illustrate the nature of trucks' daily operation. More than 75 percent of heavy-duty vehicles travel 30,000 miles or less each year (120 miles per day, assuming they operate five days per week and 50 weeks per year); 65 percent travel less than 20,000 miles each year (80 miles per day, assuming they operate five days per week and 50 weeks per year) (Figure 3). These daily distances are well within the range of existing heavy-duty electric vehicles on a single charge or tank of hydrogen—from roughly 90 miles to 500 miles or more, depending on the vehicle's make and model. Especially well-suited for electrification are fleet vehicles operating in defined areas and parked at central depots where they can recharge.

Conversely, a small percentage of vehicles, consisting almost exclusively of Class 7 and 8 semi, or tractor, trucks, travel many miles each year and account for a large fraction of the total miles traveled by heavy-duty vehicles. Vehicles with annual mileages greater than 50,000 miles (200 miles per day, assuming they operate five days per week and 50 weeks per year) make up about 10 percent of heavy-duty vehicles yet account for about 50 percent of the total miles traveled within this sector. However, many Class 7 and 8 tractors have lower annual mileages. A similar number of trucks in these categories travel less than 50,000 annual miles (45 percent) as trucks traveling more than 50,000 annual miles (55 percent).

[*Heavy-duty vehicles often travel to predictable destinations with consistent mileage, making them good candidates for electrification.*]

While semi trucks are often considered more challenging to electrify, several manufacturers (e.g., BYD, Daimler, Tesla, Volvo, Xos) have developed and are testing such vehicles in real-world operations. These demonstrations are proving it is entirely possible to electrify a vehicle segment once thought a moonshot. And recent analyses indicate similar if not lower total costs of ownership for vehicles purchased within the next 5 to 10 years, if not earlier, for electric semi trucks compared with diesel, whether operating in long haul or regional contexts (CARB 2019a; Di Filippo, Callahan, and Golestani 2019; Hall and Lutsey 2019; ICF n.d.a.; Phadke et al. 2019).

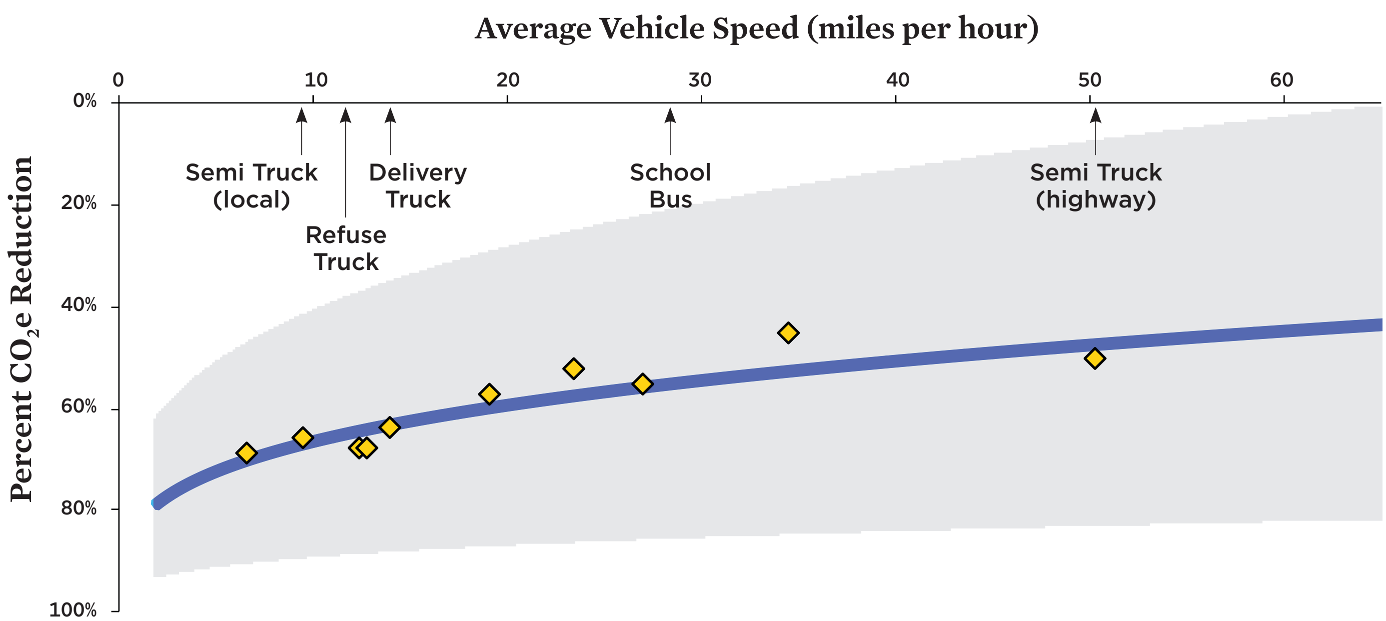
Figures 2 and 3 present average values. Some types of vehicles will operate above and others below those averages. For example, drayage trucks, which carry cargo to and from ports, railyards, and distribution centers, travel a wide range of distances depending on whether they operate near the port or travel to warehouses on the far side of the region they serve. But even considering the varied nature of truck and bus operations, the data indicate that today's technology offers opportunities for electrifying every type of heavy-duty vehicle.

ELECTRIC TRUCKS AND BUSES OFFER SIGNIFICANT CLIMATE AND AIR QUALITY BENEFITS

No matter the operating characteristics of the vehicle or electricity grid, battery-electric heavy-duty vehicles have lower global warming emissions than diesel vehicles (Figure 4). This advantage comes in addition to the public health benefits resulting from zero tailpipe emissions of harmful air pollutants such as particulate matter and nitrogen oxides.

The life cycle emissions of operating an electric vehicle compared with an internal combustion vehicle depend primarily on two factors: the vehicle's energy efficiency and the sources of electricity used to charge the vehicle. Battery-electric vehicles are considerably more energy efficient than diesel, natural gas, or gasoline vehicles, which is a major reason that electric vehicles have lower life cycle emissions than combustion vehicles, even though fossil fuels are the largest (yet declining) source of electricity in the United

FIGURE 4. Better for the Climate at Any Speed



No matter the electricity grid in the United States or the average vehicle speed, electric heavy-duty vehicles offer significant benefits toward minimizing global warming emissions compared with diesel heavy-duty vehicles. The efficiency benefits of electric heavy-duty vehicles are greatest at low average speeds, characterized by frequent acceleration and deceleration.

Notes: The gray band represents emissions reductions from the US electricity grid as a whole, from the most carbon-intensive (top edge) to the least carbon-intensive (bottom edge). The blue line shows emissions reductions of an electric vehicle on the average grid in the United States. Diamonds represent findings from studies of the energy efficiency improvements of battery-electric heavy-duty vehicles compared with diesel vehicles for a range of average speeds. Arrows show representative average speeds for different types of heavy-duty vehicles. The average speeds for the trucks listed above were determined as follows: refuse truck corresponds to real-world data collected from the operation of six front-loader trucks; delivery truck corresponds to a Class 5 stepvan tested on the Hybrid Truck Users Forum Parcel Delivery Class 4 (HTUF4) drive cycle; school bus corresponds to a 72-passenger bus tested on the Urban Driving Dynamometer Schedule for Heavy Duty Vehicles (UDDSHDV) drive cycle; local and highway semi trucks correspond to drive cycles designed to simulate drayage truck operations.

SOURCES: CARB 2018B; EPA 2018B; SANDHU ET AL. 2014; BARNITT AND GONDER 2011.

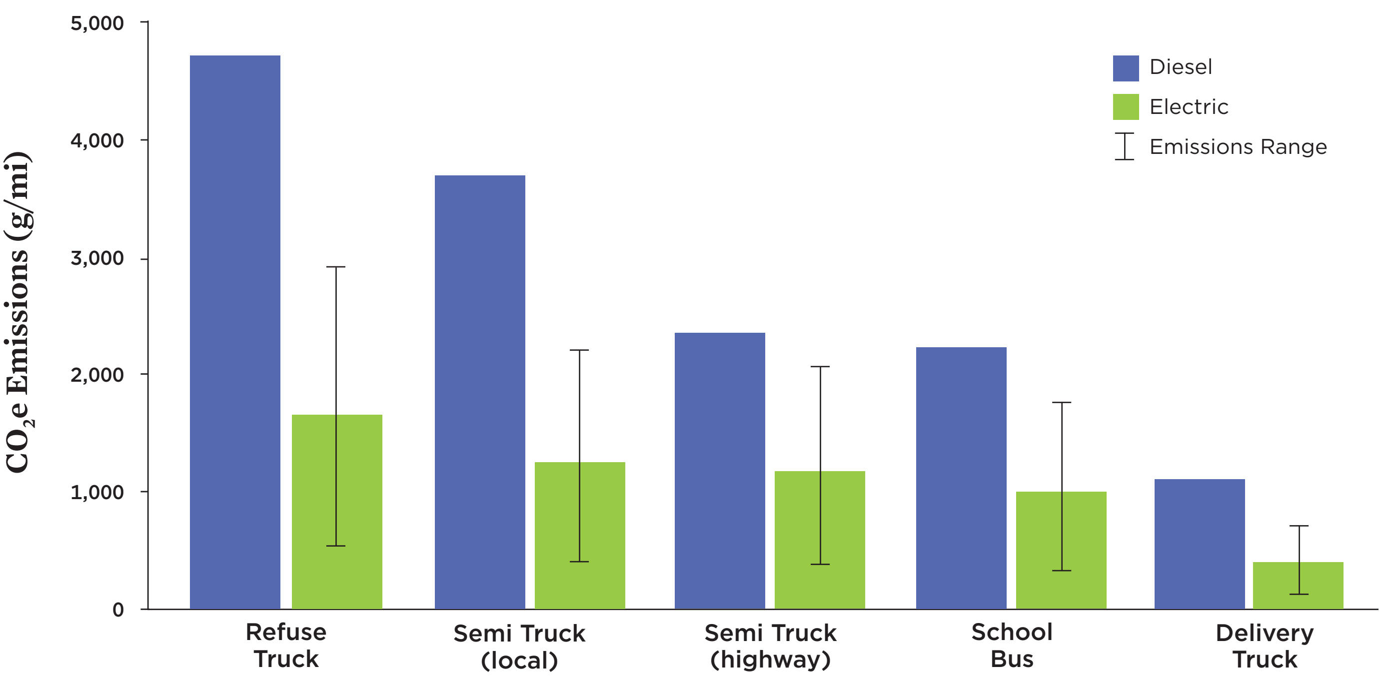
States (EIA 2019c). For trips involving frequent stopping, accelerating, or idling (average speeds of about 10 miles per hour or less), heavy-duty battery-electric vehicles are five to seven times more efficient than diesel vehicles. Even at highway speeds, heavy-duty battery-electric vehicles are 3.5 times more efficient (CARB 2018b).

The poor efficiency of combustion engines is recognizable in the heat emanating from their engines and exhausts. The heat represents chemical energy in the fuel (gasoline, diesel, or natural gas) that was not converted into mechanical energy to propel the vehicle. Energy losses are much smaller with battery-electric vehicles.

The Union of Concerned Scientists has documented the climate benefits that electric cars and transit buses offer over their combustion counterparts on all electricity grid regions in the United States (Nealer, Reichmuth, and Anair 2015; O'Dea 2018a; Reichmuth 2018). The same benefits arise for other types of heavy-duty vehicles, including delivery trucks, refuse trucks, school buses, and drayage trucks. Combining energy efficiencies for a range of vehicle types and operating characteristics with the global warming emissions associated with electricity production in every US grid region, Figure 4 shows the emissions reductions of electric vehicles traveling at average speeds ranging from 2 to 65 miles per hour (CARB 2018b).[5]

With the average sources of electricity in the United States, a heavy-duty electric vehicle reduces global warming emissions by 44 to 79 percent depending on a vehicle's average speed over the course of its trip (see the blue line in Figure 4). Using estimates of average speeds for different types of vehicles, Figure 5 shows that electric delivery trucks, refuse trucks, and locally operating semi trucks offer 65 percent reductions compared with equivalent diesel vehicles; electric semi trucks with highway-based operations and school buses offer 50 percent reductions in global warming emissions. Figure 6 (p. 8) shows the emissions reductions for a delivery truck operating in all grid regions across the

FIGURE 5. Life Cycle Global Warming Emissions for Different Heavy-Duty Electric Vehicles on the Average US Grid (generation-weighted) in 2016

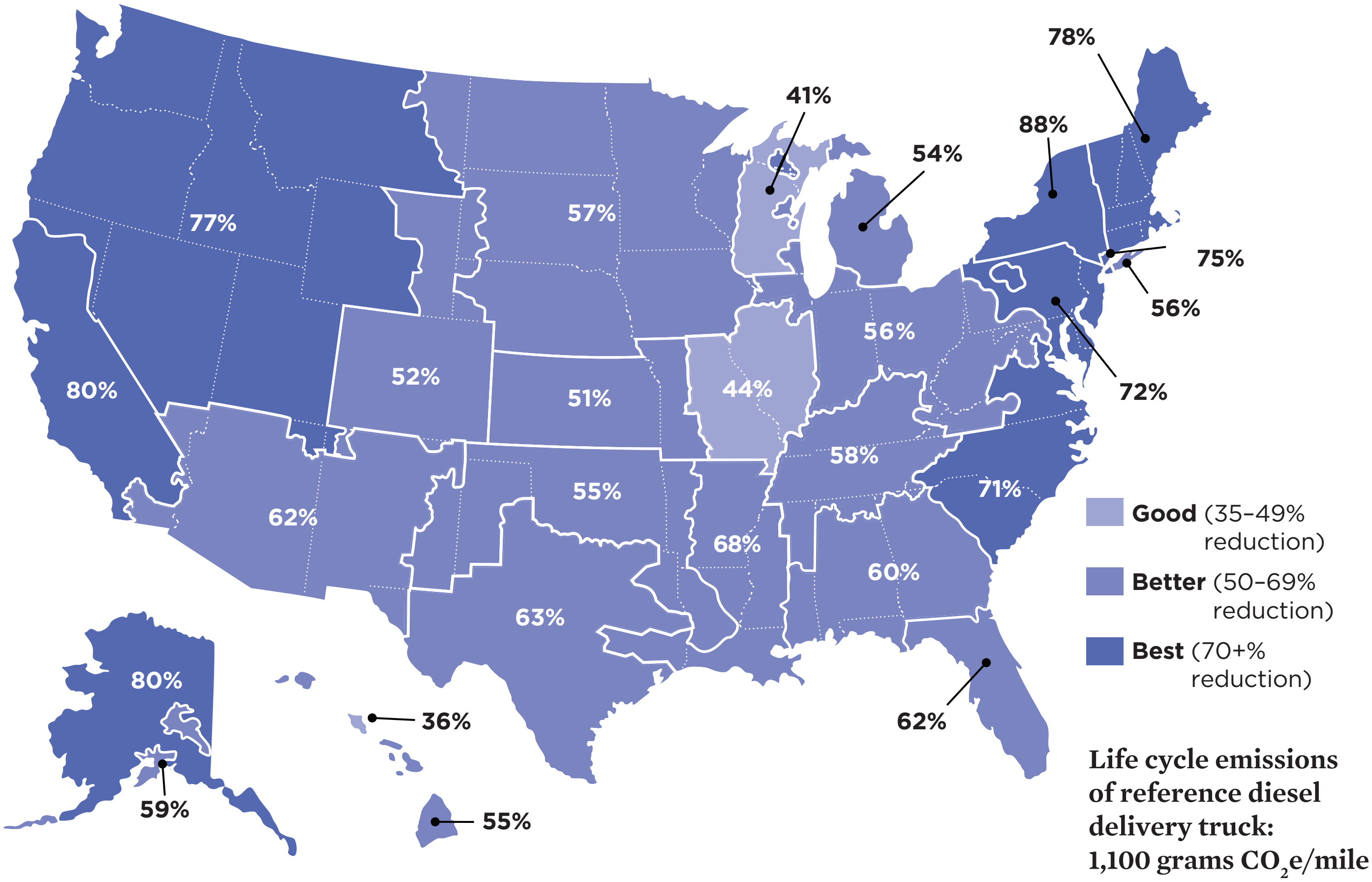


Per-mile life cycle global warming emissions vary for different types of heavy-duty vehicles depending on a vehicle's fuel efficiency. Shown are life cycle emissions from diesel and electric versions of five common heavy-duty vehicles. Bars for electric vehicles represent life cycle global warming emissions for vehicles charged on the average grid in the United States. Range bars represent emissions from the most and least carbon-intensive electricity grids in the United States.

Note: Fuel economies for the electric refuse truck and school bus were estimated based on the fuel economy of the corresponding diesel vehicle and its average speed. Fuel economies for the electric delivery truck and semi trucks were measured directly.

SOURCES: CARB 2018B; EPA 2018B; SANDHU ET AL. 2014; BARNITT AND GONDER 2011.

FIGURE 6. Electric Delivery Trucks Offer Significant Reductions in Life Cycle Global Warming Emissions in All Grid Regions of the United States



This map shows life cycle global warming emissions as a function of different sources of electricity for a common type of delivery truck (Class 5 stepvan). Percentages represent emissions reductions for the electric delivery truck compared with a similar diesel delivery truck.

SOURCES: CARB 2018B; EPA 2018B; SANDHU ET AL. 2014; BARNITT AND GONDER 2011.

United States, ranging from 36 percent to 88 percent lower life cycle global warming emissions than a diesel delivery truck.

No matter the operating characteristics of the vehicle or electricity grid, battery-electric heavy-duty vehicles have lower global warming emissions than diesel vehicles.

As the grid continues to become cleaner through commitments by states such as Hawaii, California, Nevada, New Mexico, Washington, and New York, emissions from electric vehicles will continue to decline (DSIRE 2019; Reichmuth 2018). From 2009 to 2016, global warming emissions from the production of electricity decreased by 18 percent, from 1,222 pounds CO_2e per megawatt-hour (lb/MWh) to 1,004 lb/MWh (EPA 2018b).

A Growing Market for Heavy-Duty Electric Vehicles

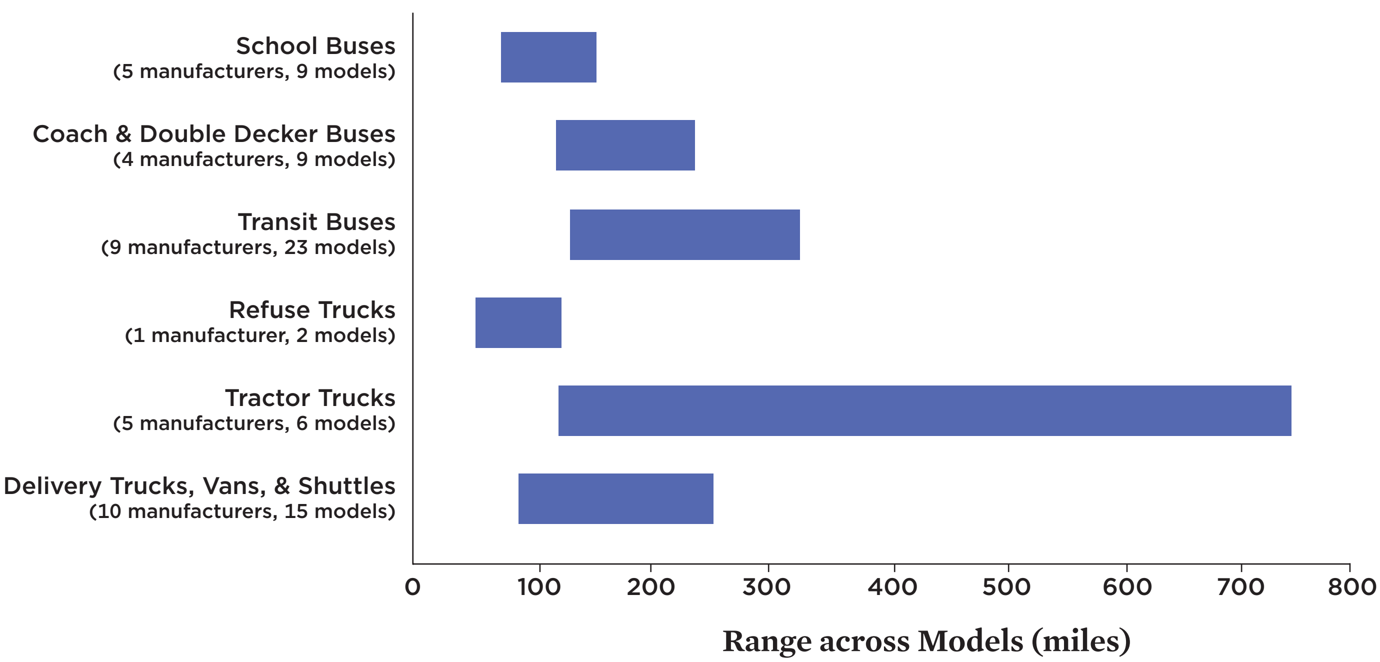
The availability of heavy-duty electric vehicles has grown rapidly in recent years (Figure 7; also see the Appendix at *www.ucsusa.org/resources/ready-work*). In the United States, there are 70 models and counting—from 27 manufacturers—of electric trucks and buses that are available today or with production announced for the next two years (see Appendix). In 2014, eight manufacturers offered 25 models of electric trucks and buses that were eligible for purchase incentives in California (HVIP 2015).

As an indicator of rapid progress in the transit bus industry, three manufacturers (BYD, New Flyer, and Proterra) offer vehicles with ranges up to, if not beyond, 200 miles, depending on the operating conditions. Five manufacturers of school buses offer electric versions, including established manufacturers and new entrants. Ten different manufacturers offer electric trucks in the delivery truck and straight truck categories. Product choices are limited for Class 7 and Class 8 trucks, yet eight manufacturers are beginning to deploy and test vehicles in these large truck categories.

New entrants dominate the heavy-duty electric vehicle market, but traditional truck manufacturers appear to be ramping up efforts on electric vehicles as well. Some of the new entrants are large companies, such as BYD and Tesla, that also produce light-duty electric vehicles. Other companies are less well-known but quickly establishing themselves. Still others are "upfitters," smaller companies filling a critical void left by original equipment manufacturers that do not offer electric versions of their vehicles. Upfitters take vehicles made by companies like Ford or GM and replace the engine with an electric drivetrain.[6] With this business model,

In the United States, there are 70 models of electric trucks and buses, from 27 manufacturers, that are available today or with production announced for the next two years.

FIGURE 7. Electric Trucks and Buses Fit Many Needs



Multiple manufacturers have electric heavy-duty trucks and buses on the road today or targeted for production within the next one to two years. The battery ranges offered by these vehicles provide numerous options for companies and municipalities interested in switching from diesel to electric models.

Notes: Mileage ranges represent the maximum value provided by manufacturers. The number of models includes those currently available for purchase and those announced for production by 2021. Excluded from the figure are yard trucks (four models available from four manufacturers) and street sweepers (two models available from one manufacturer), for which battery range is measured in hours of operation instead of miles, as well as models for which future availability is unknown. See the Appendix for detailed information on individual model ranges, battery capacity, and production status.

Jimmy O'Dea/UCS

Four manufacturers already offer electric versions of yard trucks, which move cargo containers within port, railyard, and warehouse complexes.

customers that want a Ford or Chevy truck can get it in an electric version. The disadvantage is scale, but as upfitters have established their expertise on electric drivetrains and electronics, they are beginning to partner with large vehicle manufacturers to build electric vehicles on assembly lines; this will greatly increase production rates.

ADOPTION COULD COME FAST

While deployment of heavy-duty electric vehicles on US roads lags that of electric passenger vehicles, progress in the transit bus industry is one indicator of the rate at which other heavy-duty electric vehicles could also be adopted. In the United States, electric transit buses already account for 10 percent of annual sales.[7] In contrast, passenger electric vehicles represented less than 2 percent of national automobile sales in 2018 (Auto Alliance n.d.). The rapid early adoption of electric buses stems largely from the significant investments and financial incentives provided by state and federal policies.

While electric trucks have yet to account for a significant fraction of sales in the United States, China's adoption of heavy-duty electric vehicles also indicates how quickly a transition can be made. More than 400,000 electric transit buses have been sold in China since 2012 (Albanese 2019; Eckhouse 2019). The city of Shenzhen alone has 16,000 electric transit buses (Keegan 2018). Even larger has been that city's deployment of electric vans and delivery trucks. From 2015 through 2018, Shenzhen's fleet of these vehicles expanded from nearly zero to more than 60,000. Electric models now represent about 35 percent of the city's urban delivery vehicles (McLane and Mullaney 2019).

ENERGY USE WILL SIGNIFICANTLY DECREASE, WHILE ELECTRICITY NEEDS WILL MODERATELY INCREASE

Transitioning from diesel and gasoline to electricity as the fuel for trucks and buses will decrease demand for the former fuels, and it will increase demand for electricity and hydrogen. If all trucks in the United States were suddenly battery-electric, the energy needed to power them would decline significantly. This is because electric vehicles are much more efficient than diesel, natural gas, and gasoline vehicles.

To power all these vehicles would increase overall electricity consumption. In 2017, heavy-duty vehicles on US roads consumed roughly 41 billion gallons of diesel and 10 billion gallons of gasoline (EIA 2019d). From these values, it is possible to estimate the amount of energy required to power these vehicles if they were electric. Using a vehicle efficiency improvement of four times for electric compared with diesel and accounting for efficiency losses in the transmission of electricity (6 percent) and efficiency losses associated with charging a vehicle (10 percent), it would take 560 terawatt-hours (TWh) of electricity to power all heavy-duty trucks in the United States with electricity.[8] This would represent a 13 percent increase in electricity generation compared with the 4,200 TWh used in the United States in 2017, but a 71 percent decrease in energy compared to the consumption of diesel and gasoline by heavy-duty vehicles (1,900 TWh) (EIA n.d.a; EIA n.d.b). For a sense of scale, the residential sector consumed nearly 1,400 TWh of electricity in 2017; air conditioning alone consumed more than 200 TWh (EIA n.d.c; EIA n.d.d).

Of course, electrification of trucks and buses will not occur all at once. Electrifying 10 percent of the diesel fleet over a decade would increase electricity demand similarly to the rise in demand from data servers, which increased from 35 TWh in 2000 to 70 TWh in 2008 (and then leveled off as the energy efficiency of data servers improved) (Azevedo et al. 2016). Consider, too, the speed at which the United States has added clean sources of electricity: annual generation from wind and solar increased more than 300 TWh from 2008 to 2018 (EIA 2019e).

Improving the utilization of existing sources of electricity can minimize the need for new power plants to meet increased demand from electric vehicles. Because the electricity grid is designed to accommodate the highest demand experienced on it, much of its generation capacity sits idle during periods of non-peak demand. Electric vehicles can use the idle capacity if they charge at off-peak times such as when solar or wind generate excess electricity. Better utilization of grid capacity spreads fixed costs (for example, transmission lines) over increased electricity sales, which lowers electricity rates for all customers (CUB n.d.).

Electric vehicles can provide grid services in addition to utilizing idle or curtailed generation resources. Charging at off-peak times or times of high renewable electricity generation can level out daily energy demands and reduce the need for ramping electricity generation up or down, periods that generate significant emissions (Wisland 2018). The need to reduce extreme power ramping is particularly acute in places such as California, with significant deployment of solar energy and large peaks and valleys in the daily electricity demand. Electricity rates that are lower during off-peak periods can encourage owners of electric trucks and buses to charge at times that are beneficial to the grid.

A unique aspect of electric trucks and buses compared with cars is the larger amount of instantaneous energy (power) required for charging their larger batteries. Cars currently charge at rates from 5 kW to 250 kW, with home and workplace charging falling on the slow end and "DC fast chargers," typically located at travel stops or public charging stations, representing the fast end. For trucks and buses, whose batteries can store anywhere from 2 to 10 times the amount of energy simply by having more battery cells, rates of 20 kW to 200 kW are used for overnight charging depending on the size of the vehicle's battery. Even faster on-route chargers used by some transit buses charge at 150 kW to 400 kW (Proterra 2019). Charging at lower power rates and at times with lower demand from other sources is optimal for the grid. One strategy that can lessen impacts on the grid is to charge a vehicle's battery from stationary batteries built into charging stations.

The Economic Case for Heavy-Duty Electric Vehicles

Fuel and maintenance savings can offset the higher upfront costs of heavy-duty electric vehicles, making them cheaper than a diesel or natural gas vehicle over the life of a vehicle. This is especially the case for higher mileage truck and bus applications: for these, fuel costs can greatly exceed vehicle costs—more than twice as much depending on the application. The economics shift even further in favor of electric vehicles as the prices of batteries and fuel cells decrease and the prices of diesel and natural gas engines increase to meet clean air standards.

[Depending on the application, battery-electric trucks can be cost-competitive today.]

Depending on the application, battery-electric trucks can be cost competitive with diesel today on a total-cost-of-ownership basis. In nearly every vehicle case examined, including long-haul semi trucks, battery-electric trucks and buses are cheaper than diesel vehicles on a total-cost-of-ownership basis for vehicles purchased within the next 10 years (CARB 2019a; Hall and Lutsey 2019; ICF n.d.a.; Phadke et al. 2019). Those are the conclusions of recent analyses conducted by the California Air Resources Board, the International Council on Clean Transportation, and ICF. The studies, summarized in Figures 8 and 9, analyzed the total cost of ownership for vehicles purchased today and in 2030 for Class 6 delivery trucks and Class 8 short-haul semi trucks. All three studies reached similar conclusions despite different assumptions for many parameters including vehicle purchase prices, annual mileage, years of vehicle ownership, maintenance costs, electricity rates, and vehicle fuel efficiencies.

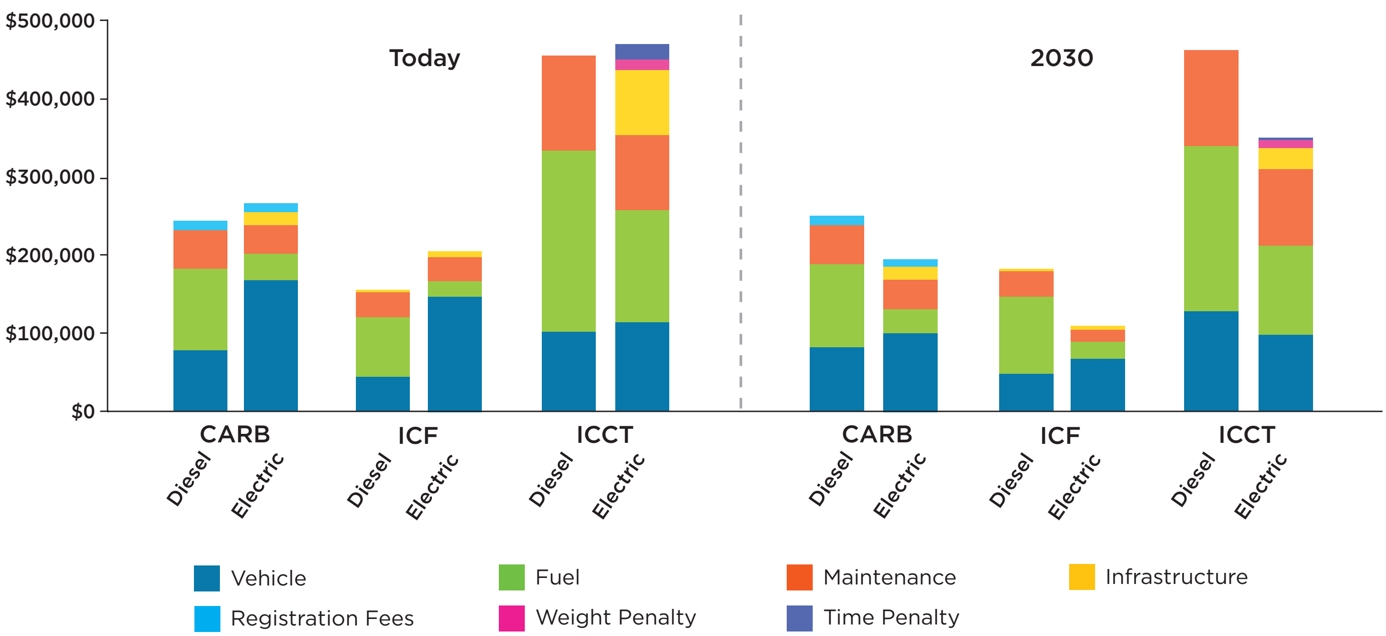
The largest impact comes from savings on fuel costs: compared with diesel, electricity reduces fuel costs an estimated 30 to 75 percent, depending on assumptions for vehicle efficiency and fuel prices. In most scenarios examined, the vehicle purchase price remains higher than that of its diesel counterpart through 2030, yet total ownership costs are significantly lower.

All three analyses focus on California, which allows for comparable assumptions for electricity rates and diesel costs. Otherwise, the cost assumptions apply to all markets in the United States.[9] Given that California's electricity rates are among the nation's highest, electric vehicles would offer even greater fuel savings elsewhere.[10]

While California's policies and incentives significantly offset the costs of vehicle purchases, fuel, and charging infrastructure, Figures 8 and 9 exclude these financial benefits as they are not currently available in other states (HVIP 2019; O'Dea 2019a; Barbose and Martin 2018). With California's policies and incentives, however, the total cost of ownership is lower than diesel today for 19 of 20 vehicle scenarios examined in the three studies. The scenarios include several types of delivery trucks, semi trucks, transit buses, and school buses. Vehicle applications with the least savings are those with lower annual mileages and higher operating speeds, which offer less improvement in fuel efficiency compared with diesel vehicles. California's Low Carbon Fuel Standard, which financially penalizes fuels with carbon intensities above a set standard and rewards fuels below it, can lower the electricity rates for heavy-duty vehicles approximately \$0.09 to \$0.14 per kWh today and \$0.07 to \$0.12 per kWh in 2030, depending on the fuel efficiency improvements of an electric vehicle compared with a diesel vehicle.[11]

The three studies also examined the total cost of ownership for hydrogen fuel cell vehicles (not shown in Figures 8 and 9). Fuel cell vehicles have higher total costs of ownership compared with battery-electric vehicles across all vehicle types today. Significant reductions in the costs of fuel cells

FIGURE 8. Total Cost Comparisons, Class 6 Delivery Trucks

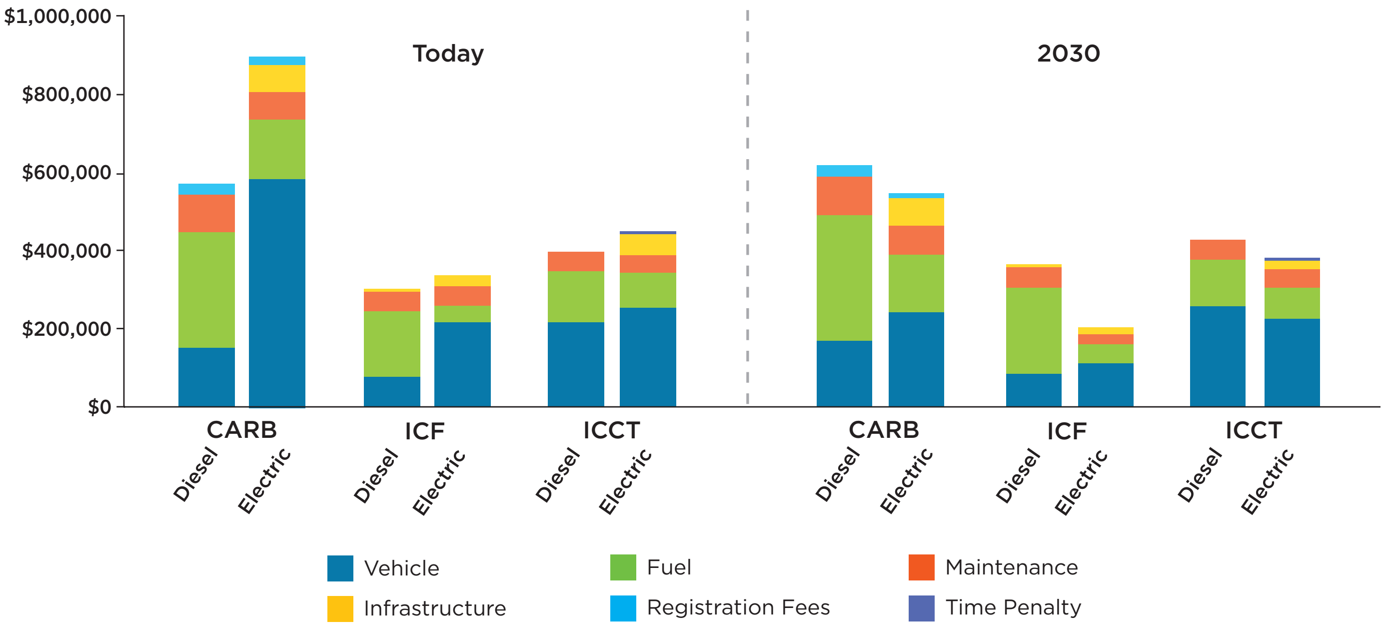


The total cost of ownership for Class 6 electric delivery trucks is competitive with diesel vehicles today and estimated to be significantly lower within the next decade.

Notes: In the ICCT study, "today" corresponds to 2020; in the CARB and ICF studies, 2018. Vehicle costs in the ICF and CARB analyses account for the residual value of the vehicle at the end of its assumed period of ownership.

SOURCES: HALL AND LUTSEY 2019; ICF N.D.A, CARB 2019A.

FIGURE 9. Total Cost Comparisons, Class 8 Short-Haul/Drayage Trucks



The total cost of ownership for Class 8 electric short-haul/drayage trucks can be lower than diesel today with financial incentives, and is estimated to be lower for diesel trucks within the next decade without such incentives.

Notes: In the ICCT study, "today" corresponds to 2020; in the CARB and ICF studies, 2018. Vehicle costs in the ICF and CARB analyses account for the residual value of the vehicle at the end of its assumed period of ownership.

SOURCES: HALL AND LUTSEY 2019: ICF N.D.A, CARB 2019A.

and hydrogen are needed for these vehicles to compete with diesel vehicles (see Box 3).

How to Get More Electric Trucks and Buses on the Road

Considering their local operating characteristics, the range of today's battery technologies, and similar if not reduced ownership costs, widespread electrification makes immediate sense in several classes of heavy-duty vehicles. However, internal combustion engines have dominated the truck and bus marketplace for more than a century, presenting significant barriers to transforming these markets. Policies are needed to shift from an industry dominated by diesel to one powered by electricity or hydrogen.

Three types of policy are important to deploying heavy-duty electric vehicles: financial incentives, infrastructure investments, and manufacturing and purchasing standards. All of these policies must center on improving air quality in communities most burdened by pollution from vehicles.

FINANCIAL INCENTIVES

Overcoming the higher upfront cost of electric trucks is an important strategy for increasing their adoption. For example, a federal tax credit that provides up to $7,500 has been key

BOX 3.

What About Fuel Cells?

Batteries and fuel cells both generate electricity that an electric motor converts to mechanical energy to move a vehicle. Batteries use compounds of lithium and graphite to produce electricity, while fuel cells produce electricity from hydrogen and oxygen gases. Both types of electric vehicles have zero tailpipe emissions and are significantly more energy efficient than heavy-duty vehicles powered by diesel or natural gas. The main advantage of fuel cells over batteries are shorter fueling times, but higher vehicle and fuel prices have slowed their commercialization compared with battery electric vehicles.

Jimmy O'Dea/UCS

Electric school buses can reduce global warming emissions by about 50 percent compared with diesel buses, based on the US average grid mix. Five manufacturers offer electric school buses today.

Electric utilities and utility regulators should ensure that heavy-duty vehicle operators have access to fair rates that account for these vehicles' demands and benefits to the grid.

in reducing the upfront cost of passenger electric vehicles. No similar federal policy exists for electric trucks and buses, but California's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) has demonstrated that incentives to lower the upfront cost of electric vehicles can accelerate adoption. This program has funded more than 2,400 electric vehicles over the past nine years and vehicle demand annually exceeds the allocated state funding (CARB 2019b).

Policy strategies to reduce the upfront costs of electric trucks and buses include establishing federal and state tax credits or rebates, or waiving federal, state, and local sales taxes for the purchase of these vehicles. While 11 states and Washington, DC, have incentives for buying electric passenger vehicles, only California, Colorado, New York, Texas, and Utah offer incentives for buying heavy-duty electric vehicles (Colorado Department of Revenue 2019; HVIP 2019; NYTVIP n.d.; Tesla n.d.; TCEQ n.d.; 59 Utah Code).[12] Other states could do this also, and design programs to ensure deployment of electric trucks and buses occurs in communities most affected by air pollution. Requirements for the amount of funding that benefits these communities and higher incentives for electric trucks and buses deployed there, as set forth in California's HVIP program, can ensure that air quality benefits occur where they are needed most.

In addition to reducing upfront costs, incentives to lower the operating expenses of electric vehicles compared with diesel can also help make a more compelling business case to go electric. Several policy strategies exist in this regard.

Ensure fair and reasonable electric utility rates for truck and bus charging: Most commercial electricity rates were designed without electric trucks and buses in mind. However, these vehicles place different demands on, and offer different services to, the electricity grid compared with buildings and equipment traditionally associated with commercial electricity use (Houston 2019). Electric utilities and utility regulators should ensure that heavy-duty vehicle operators have access to fair rates that account for these vehicles' demands and benefits to the electric grid. Such rates would provide the opportunity for vehicle operators to save on fuel costs, especially operators that charge trucks or buses at off-peak times and during periods when renewable electricity generation is high.

Establish state-level clean fuels standards: In state programs like California's Low Carbon Fuel Standard and Oregon's Clean Fuel Program, fleets can earn clean-fuel credits for electric operation and sell those into a credit market (Barbose and Martin 2018). The credits can add up. For example, an electric transit bus in California can generate

Dennis Schroeder/NREL

Powering trucks and buses with electricity is not only better for the climate than diesel—even in the most carbon-intensive electricity grid regions of the United States—but also offers significant savings in fuel costs.

more than $10,000 of credits annually, lowering its electricity rate by $0.14 per kWh.

Include electricity in federal fuels policy: Current federal policy supports increased use of biodiesel and biomethane, but it does not provide equivalent support for the use of electricity, even if that electricity is produced from biomethane. Creating pathways for electricity under existing or future fuels policy would provide incentives for electrification commensurate with those available to biodiesel and biomethane.

Create low- or zero-emissions zones: Cities seeking to accelerate the adoption of electric trucks could implement fees on higher-emitting trucks or provide preferred access to electric trucks. The Port of Los Angeles and the Port of Long Beach have committed to plans that will charge diesel and natural gas trucks to access the ports, while exempting electric trucks. While the strategy is not prevalent in the United States, low-emissions zones, where fees or exclusions apply to higher polluting commercial vehicles, are prominent in European cities (European Union n.d.). Similarly, states can incentivize electric truck adoption by reducing or waiving annual registration fees.

INVESTMENTS IN CHARGING INFRASTRUCTURE

Successfully deploying electric trucks will require investments in charging infrastructure. In the near term, financial support for installing charging infrastructure can encourage fleets to adopt electric trucks and reduce the upfront costs of transitioning to electric vehicles. Utilities' and utility regulators' support for investments in charging infrastructure can catalyze truck electrification as can federal policy.

Utility investments: In addition to offering fair and affordable electricity rates, utilities have a significant role to play in the widespread electrification of heavy-duty vehicles by investing in charging infrastructure (Houston 2019). Many utilities have begun implementing programs to facilitate the adoption of electric trucks and buses. These include installing and upgrading infrastructure on customers' sites (upgrading electric panels, trenching, installing wiring) or offering rebates for infrastructure improvements. Utilities could also consider financing options that allow their customers to pay back the cost of infrastructure installations on future utility bills. Such programs should provide greater support for charging facilities in communities affected by pollution to ensure that clean air benefits come where they are most needed.

State and federal support for truck charging infrastructure: For electric trucks to reach their potential, publicly accessible charging/fueling sites on major travel corridors will need to complement depot-based charging and

[Utilities have a significant role to play in the widespread electrification of heavy-duty vehicles.]

hydrogen fueling infrastructure. For example, the West Coast Clean Transit Corridor is a regional effort by several utilities and agencies across state lines to determine the infrastructure needs for long-haul electric trucking on the Interstate 5 corridor (SMUD 2019). State and federal policymakers can support such efforts by providing grants or other financial incentives to promote coordination and spur the installation of robust charging networks.

GOALS AND STANDARDS

While financial incentives can encourage the early adoption of technologies, it also will take standards, laws, and regulatory measures to accelerate the adoption of electric trucks and buses. This "carrot and stick" strategy has succeeded in the market for passenger electric vehicles. California's disproportionate share of electric cars in the United States illustrates the impact of these strategies. Despite having 11 percent of US vehicles and 12 percent of the nation's population, California has roughly 50 percent of the million-plus electric cars sold in the country (including plug-in hybrids) (FHWA 2019; Auto Alliance n.d.; USCB n.d.).

The main reason California is a leader in electric cars is state policy (UCS 2019). In addition to incentive and infrastructure policies, California requires car manufacturers to sell electric vehicles in the state, and it is considering a similar requirement for truck manufacturers.

Beyond such a requirement, policymakers can consider ways to compel fleets—whether public or private—to transition to electric. California recently adopted measures to require transit agencies and companies operating airport shuttle buses to move toward electrifying their fleets over the next decade (O'Dea 2019b; O'Dea 2018b). Similar measures targeting port drayage trucks and delivery vehicles are expected.

Local governments can also adopt policies for electrifying municipal trucks and buses. Contracts for refuse services or school bus services could include targets for deploying electric vehicles. Several transit agencies' boards have approved plans to transition their entire fleets to electric. Such fleet requirements can increase sales volumes, and thereby lower costs, and drive investments in charging infrastructure. In all, no one policy will lead to the widespread electrification of trucks and buses. Instead it will take key policies that lower costs, support charging infrastructure, and set standards for the availability and adoption of electric trucks and buses.

***Jimmy O'Dea** is a senior vehicles analyst in the UCS Clean Transportation Program.*

ACKNOWLEDGMENTS

This report was made possible by the generous support of the Common Sense Fund, the 11th Hour Project of the Schmidt Family Foundation, the Farvue Foundation, the William and Flora Hewlett Foundation, the John D. and Catherine T. MacArthur Foundation, the John Merck Fund, and UCS members.

The author thanks Gideon Weissman at Frontier Group; and Don Anair, Dave Cooke, and Samantha Houston at UCS for helpful feedback and discussions.

Organizational affiliations are listed for identification purposes only. The opinions expressed herein do not necessary reflect those of the organizations that funded the work or the individuals who reviewed it. The Union of Concerned Scientists bears sole responsibility for the report's contents.

ENDNOTES

1 *Transportation emissions exclude those related to the production of fuels (e.g., diesel and gasoline). On-road sources of emissions represent 24 percent of total US global warming emissions; aircraft, ships, boats, rail, pipelines, and lubricants comprise 5 percent. Heavy-duty vehicles defined in the EPA's emissions inventory include vehicles with gross vehicle ratings of 8,501 pounds (Class 2b) and above. For consistency with vehicle population and NO_x and $PM_{2.5}$ emissions, global warming emissions represent data from 2014. For the latest data available (2017), the fraction of global warming emissions from heavy-duty vehicles relative to all on-road vehicles (30 percent) remains similar to the 2014 values cited in the text. Overall emissions from both heavy- and light-duty vehicles increased from 2014 to 2017, from 421 to 451 million metric tons of CO_2e (EPA 2019).*

2 *The population of Class 2b–8 heavy-duty vehicles was determined by combining an estimate of the Class 2b population (13.1 million vehicles) from the US Department of Energy and the Class 3–8 population (12.9 million vehicles) from the Federal Highway Administration, including buses (EIA 2016; FHWA 2016). Vehicle population represents that in 2014 to match the latest NO_x and $PM_{2.5}$ emissions data. Using data from the EIA's 2019 Annual Energy Outlook and the FHWA's Highway Statistics 2017, the population of Class 2b and Class 3–8 vehicles in 2017, the latest data available, is 13.8 million vehicles for each category, or 10 percent of total vehicles as in 2014 (EIA 2019a; FHWA 2019). Previous UCS analyses found Class 2b–8 vehicles comprise 7 percent of total vehicles (Chandler, Espino, and O'Dea 2016; Cooke 2015). Data in the EIA's 2016 Annual Energy Outlook and later show significantly more Class 2b vehicles than previously estimated, explaining the increase.*

3 *Transportation, including off-road modes, is the largest source of NO_x emissions in the United States. Heavy-duty vehicles account for 30 percent of the transportation sector's NO_x emissions and 16 percent of all NO_x emissions. For $PM_{2.5}$, heavy-duty vehicles account for 28 percent of transportation's emissions, but less than 2 percent of all $PM_{2.5}$ emissions including dust and fire sources (EPA 2018a). Diesel particulate matter, however, remains a critical pollutant to minimize as it has been classified as a carcinogen by the World Health Organization (CARB n.d.).*

4 *Excluding Class 2b vehicles does not significantly affect the fraction of vehicles with operating ranges less than 50 or 100 miles. Eighty percent of Class 3–8 trucks have a primary operating range of less than 100 miles; 63 percent have an operating range of less than 50 miles. An updated survey of heavy-duty vehicles in California found similar weighted-distributions of vehicle population (by truck class and vehicle age) and vehicle miles traveled (by truck class, but not commodity) from 2002 and 2017, suggesting results from the 2002 vehicle inventory and use survey (VIUS) still roughly reflect present-day trends in the truck industry in the absence of a newer national VIUS and despite a small sample size for pickup trucks in the 2002 survey (Komanduri 2019; Birky et al. 2017).*

5 *The average truck speed on interstate highways is 50 to 60 miles per hour (DOT n.d.; EERE n.d.).*

6 *Sometimes the company arranges to procure vehicles without the engine, which is preferable.*

7 *Annual sales of standard and articulated transit buses averaged 4,400 per year over the last five years (2012–2016) (FTA 2018). This number of sales reflects a 14-year lifespan, or a 7 percent annual turnover compared with the 63,300 total buses. The number of electric buses awarded, as tracked by the Center for Transportation and the Environment, increased from roughly 400 in 2015 to 800 in 2016, 1,200 in 2017, and 1,600 in 2018 (Raudebaugh 2018). The number of electric buses deployed, awarded, or on order as tracked by CALSTART increased from 1,650 in 2018 to 2,255 in 2019 (Silver, Jackson, and Lee 2019; Popel 2018). Whether considering just new awards or a combination of new awards, orders, and deployed buses, sales of electric buses already exceed 10 percent of annual sales.*

8 *Electric heavy-duty vehicles are three to eight times more energy efficient than comparable diesel vehicles, depending on the nature of the vehicle's operation, namely its average speed (CARB 2018b).*

9 *The CARB and ICF analyses used statewide averages for electricity rates; the ICCT study used rates specific to Southern California Edison.*

10 *Only Alaska and Hawaii have higher electricity rates than California. Connecticut has similar if not slightly lower electricity rates than California. Electricity is roughly 50 percent cheaper in most other states compared with California (EIA n.d.e). While diesel is also more expensive in California than other states, the price differential is less than electricity, roughly 15 percent (EIA n.d.f).*

11 *Estimates of Low Carbon Fuel Standard revenues use credit values of \$100 per metric ton of CO_2e and a carbon intensity of electricity in California of 93.11 grams CO_2e per megajoule (MJ) in 2019 (based on the California Energy Commission's grid mix for 2019), and 54.43 grams CO_2e per MJ in 2030 (based on the California Public Utilities Commission's Integrated Resource Plan) (ICF n.d.b.).*

12 *State incentives for the purchase of electric vehicles listed in the text exclude programs funded through the Volkswagen Environmental Mitigation Trust. Maine offers incentives for the purchase of electric passenger vehicles with this funding and several states offer incentives for the purchase of electric trucks and buses with this funding (Efficiency Maine n.d.).*

REFERENCES

40 US Code CFR § 86.082-2. Electronic code of federal regulations (e-CFR), Title 40. Protection of environment, Chapter I. Environmental Protection Agency, Subchapter C. Air programs, Part 86. Control of emissions from new and in-use highway vehicles and engines, Subpart A. General provisions for heavy-duty engines and heavy-duty vehicles, Section 86.082-2. Definitions. Online at *www.law.cornell.edu/cfr/text/40/86.082-2*, accessed November 15, 2019.

59 Utah Code §7.618. Title 59. Revenue and Taxation, Chapter 7. *Corporate Franchise and Income Taxes, Part 6. Credits, Section 618. Tax credit related to alternative fuel heavy duty vehicles.* Online at *https://le.utah.gov/xcode/Title59/Chapter7/59-7-S618.html?v=C59-7-S618_2017050920170509*, accessed November 20, 2019.

Albanese, N. 2019. Oral presentation, Zero-Emission Bus Conference, San Francisco, CA. September 26.

Alternative Fuels Data Center (AFDC). No date. Vehicle weight classes & categories. Washington, DC: US Department of Energy. Online at *https://afdc.energy.gov/data/10380,* accessed September 23, 2019.

American Lung Association (ALA). 2019. State of the air. Online at *www.lung.org/assets/documents/healthy-air/state-of-the-air/sota-2019-full.pdf*, accessed October 1, 2019.

Atlas Public Policy. No date. National EV market. Online at *www.atlasevhub.com/materials/national-ev-sales* (subscription required), accessed October 1, 2019.

Auto Alliance. No date. Advanced technology vehicle sales dashboard. Online at *https://autoalliance.org/energy-environment/advanced-technology-vehicle-sales-dashboard,* accessed September 23, 2019.

Azevedo, I., R. Brown, M. Herrlin, N. Horner, J. Koomey, W. Lintner, E. Masanet, S. Shehabi, S. Smith, and D. Sartor. 2016. *United States Data Center energy usage report*. Berkeley, CA: Lawrence Berkeley National Laboratory.

Barbose, J., and J. Martin. 2018. California's clean fuel standard boosts the electric vehicle market. Cambridge, MA: Union of Concerned Scientists. Online at *www.ucsusa.org/resources/californias-clean-fuel-standard-boosts-electric-vehicle-market,* accessed October 8, 2019.

Barnitt, R., and J. Gonder. 2011. Drive cycle analysis, measurement of emissions and fuel consumption of a PHEV school bus. NREL/CP-5400-50251. Golden, CO: National Renewable Energy Laboratory. Online at *www.nrel.gov/docs/fy11osti/50251.pdf*, accessed November 21, 2019.

Birky, A., M. Laughlin, K. Tartaglia, R. Price, B. Lim, and Z. Lin. 2017. Electrification beyond light duty: Class 2b-3 commercial vehicles. Oak Ridge, TN: Oak Ridge National Laboratory. Online at *https://info.ornl.gov/sites/publications/Files/Pub72938.pdf,* accessed September 23, 2019.

Caiazzo, F., A. Ashok, I.A. Waitz, S.H.L. Yim, and S.R.H. Barrett. 2013. Air pollution and early deaths in the United States. Part I: Quantifying the impact of major sectors in 2005. *Atmospheric Environment* 79:198–208. doi:10.1016/j.atmosenv.2013.05.081.

California Air Resources Board (CARB). 2019a. Advanced Clean Trucks: Total cost of ownership discussion document. Sacramento, CA. Online at *http://ww2.arb.ca.gov/sites/default/files/2019-02/190225tco_0.pdf,* accessed October 8, 2019.

California Air Resources Board (CARB). 2019b. Public workshop on the fiscal year 2019–20 funding plan for clean transportation incentives for low carbon transportation investments and air quality improvement program: Discussion document. Sacramento, CA. Online at http:*//ww2.arb.ca.gov/sites/default/files/2019-06/fy1920lct-discussiondoc.pdf,* accessed September 23, 2019.

California Air Resources Board (CARB). 2018a. Emission Factors (EMFAC) model v1.0.2. Accessed May 20, 2019. Online at *www.arb.ca.gov/emfac/2017.*

California Air Resources Board (CARB). 2018b. Battery electric truck and bus energy efficiency compared to conventional diesel vehicles. Sacramento, CA. Online at *http://ww2.arb.ca.gov/resources/documents/advanced-clean-trucks-battery-electric-truck-and-bus-energy-efficiency-paper.*

California Air Resources Board (CARB). No date. Summary: Diesel particulate matter health impacts. Online at *http://ww2.arb.ca.gov/resources/summary-diesel-particulate-matter-health-impacts*, accessed November 16, 2019.

Citizens Utility Board (CUB). No date. The ABCs of EVs: A guide for policy makers and consumer advocates. Chicago, IL. Online at *https://citizensutilityboard.org/wp-content/uploads/2017/04/2017_The-ABCs-of-EVs-Report.pdf,* accessed October 8, 2019.

Colorado Department of Revenue. 2019. Income 69: Innovative motor vehicle and innovative truck credits. Online at *www.colorado.gov/pacific/sites/default/files/Income69.pdf*, accessed November 20, 2019.

Cooke, D. 2015. *Engines for change: From cell phones to sodas, how new truck standards can improve the way America ships goods.* Cambridge, MA: Union of Concerned Scientists. Online at *www.ucsusa.org/resources/engines-change,* accessed September 23, 2019.

Darrow, L.A., M. Klein, W.D. Flanders, L.A. Waller, A. Correa, M. Marcus, J.A. Mulholland, A.G. Russell, and P.E. Tolbert. 2009. Ambient air pollution and preterm birth: A time-series analysis. *Epidemiology* 20(5):689–698. doi:10.1097/EDE.0b013e3181a7128f.

Database of State Incentives for Renewables and Efficiency (DSIRE). 2019. Renewable and clean energy standards. Raleigh, NC: North Carolina Clean Energy Technology Center. Online at *https://s3.amazonaws.com/ncsolarcen-prod/wp-content/uploads/2019/07/RPS-CES-June2019.pdf,* accessed September 23, 2019.

Davis, S.C., S.E. Williams, R.G. Boundy, and S. Moore. 2017. 2016 vehicle technologies market report. Oak Ridge, TN: Oak Ridge National Laboratory. Online at *https://tedb.ornl.gov/wp-content/uploads/2019/04/2016_Vehicle_Technologies_Market_Report.pdf, accessed November 15, 2019*.

Di Filippo, J., C. Callahan, and N. Golestani. 2019. Zero-emission drayage trucks: Challenges and opportunities for the San Pedro Bay ports. Los Angeles, CA: University of California–Los Angeles. Online at *https://innovation.luskin.ucla.edu/wp-content/uploads/2019/10/Zero_Emission_Drayage_Trucks.pdf,* accessed October 31, 2019.

Eckhouse, B. 2019. The U.S. has a fleet of 300 electric buses. China has 421,000. Bloomberg, May 15. Online at *www.bloomberg.com/news/articles/2019-05-15/in-shift-to-electric-bus-it-s-china-ahead-of-u-s-421-000-to-300*, accessed October 8, 2019.

Efficiency Maine. No date. EV Accelerator. Online at *www.efficiencymaine.com/ev/drive-electric*, accessed November 20, 2019.

Energy Information Administration (EIA). 2019a. Annual Energy Outlook 2019: Table: Transportation fleet car and truck stock by type and technology. Washington, DC: US Department of Energy. Online at *www.eia.gov/outlooks/aeo/data/browser/#/?id=55-AEO2019&sourcekey=0,* accessed November 16, 2019.

Energy Information Administration (EIA). 2019b. Annual Energy Outlook 2019: Table: Light-duty vehicle stock by technology type. Washington, DC: US Department of Energy. Online at *https://www.eia.gov/outlooks/aeo/data/browser/#/?id=49-AEO2019&cases=ref2019&sourcekey=0,* accessed November 15, 2019.

Energy Information Administration (EIA). 2019c. What is US electricity generation by energy source? Washington, DC: US Department of Energy. Online at *www.eia.gov/tools/faqs/faq.php?id=427&t=3*, accessed October 25, 2019.

Energy Information Administration (EIA). 2019d. Annual Energy Outlook 2019: Table: Transportation sector energy use by fuel type within a mode. Washington, DC: US Department of Energy. Online at *www.eia.gov/outlooks/aeo/data/browser/#/?id=46-AEO2019&region=0-0&cases=ref2019&start=2017&end=2019&f=A&linechart=ref2019-d111618a.2-46-AEO2019&sourcekey=0*, accessed September 23, 2019.

Energy Information Administration (EIA). 2019e. U.S. renewable electricity generation has doubled since 2008. Today in Energy, March 19. Washington, DC: US Department of Energy. Online at *www.eia.gov/todayinenergy/detail.php?id=38752,* accessed September 23, 2019.

Energy Information Administration (EIA). 2016. Annual Energy Outlook 2016: Transportation fleet car and truck stock by type and technology. Washington, DC: US Department of Energy. Online at *www.eia.gov/outlooks/aeo/data/browser/#/?id=55-AEO2016&sourcekey=0,* accessed November 16, 2019.

Energy Information Administration (EIA). No date a. Table 1.1. Total electric power industry summary statistics, 2017 and 2016. Washington, DC: US Department of Energy. Online at *www.eia.gov/electricity/annual/html/epa_01_01.html,* accessed September 23, 2019.

Energy Information Administration (EIA). No date b. Frequently asked questions: What is U.S. electricity generation by energy source? Washington, DC: US Department of Energy. Online at *www.eia.gov/tools/faqs/faq.php?id=427&t=3,* accessed September 23, 2019.

Energy Information Administration (EIA). No date c. Electricity data browser: Retail sales of electricity. Washington, DC: US Department of Energy. Online at *www.eia.gov/electricity/data/browser/#/topic/5?agg=0,1&geo=g&endsec=vg&linechart=ELEC.SALES.US-ALL.A~ELEC.SALES.US-RES.A~ELEC.SALES.US-COM.A~ELEC.SALES.US-IND.A&columnchart=ELEC.SALES.US-ALL.A~ELEC.SALES.US-RES.A~ELEC.SALES.US-COM.A~ELEC.SALES.US-IND.A&map=ELEC.SALES.US-ALL.A&freq=A&ctype=linechart&ltype=pin&rtype=s&maptype=0&rse=0&pin=,* accessed September 23, 2019.

Energy Information Administration (EIA). No date d. Frequently asked questions: How is electricity used in U.S. homes? Washington, DC: US Department of Energy. Online at *www.eia.gov/tools/faqs/faq.php?id=96&t=3*, accessed September 23, 2019.

Energy Information Administration (EIA). No date e. Average retail price of electricity, monthly. Washington, DC: US Department of Energy. Online at *www.eia.gov/electricity/data/browser/#/topic/7?agg=1,0&geo=00fvvvvvvvvvo&endsec=fg&freq=M&start=200101&end=201908&ctype=linechart&ltype=pin&rtype=s&maptype=0&rse=0&pin=*, accessed November 20, 2019.

Energy Information Administration (EIA). No date f. Petroleum: Data—Weekly retail gasoline and diesel prices. Online at *www.eia.gov/dnav/pet/pet_pri_gnd_a_epd2d_pte_dpgal_a.htm,* accessed September 23, 2019.

Environmental Protection Agency (EPA). 2019. Inventory of US greenhouse gas emissions and sinks. Washington, DC. Online at *www.epa.gov/sites/production/files/2019-04/documents/us-ghg-inventory-2019-main-text.pdf*, accessed October 8, 2019.

Environmental Protection Agency (EPA). 2018a. National Emissions Inventory, 2014 Version 2. Washington, DC. Online at *www.epa.gov/air-emissions-inventories/2014-national-emissions-inventory-nei-data*, accessed October 8, 2019.

Environmental Protection Agency (EPA). 2018b. Emissions and generation resource integrated database (eGRID). Washington, DC. Online at *www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid,* accessed October 8, 2019.

European Union. No date. Urban access regulations in Europe. Online at *https://urbanaccessregulations.eu*, accessed November 16, 2019.

Federal Highway Administration (FHWA). 2019. Highway statistics 2017. Washington, DC: US Department of Transportation. Online at *www.fhwa.dot.gov/policyinformation/statistics/2017/vm1.cfm,* accessed October 8, 2019.

Federal Highway Administration (FHWA). 2016. Highway Statistics 2014. Washington, DC: US Department of Transportation. Online at *www.fhwa.dot.gov/policyinformation/statistics/2014,* accessed October 8, 2019.

Federal Motor Carrier Safety Administration (FMCSA). 2017. Drivers: Overview. Washington, DC: Federal Highway Administration, US Department of Transportation. Online at *www.fmcsa.dot.gov/registration/commercial-drivers-license/drivers*, accessed September 23, 2019.

Federal Transit Administration (FTA). 2018. National Transit Database: 2017 Fuel and Energy. Washington, DC: US Department of Transportation. Online at *www.transit.dot.gov/ntd/data-product/2017-fuel-and-energy,* accessed October 8, 2019.

Hall, D., and N. Lutsey. 2019. Estimating the infrastructure needs and costs for the launch of zero-emission trucks. Washington, DC: The International Council on Clean Transportation. Online at *https://theicct.org/sites/default/files/publications/ICCT_EV_HDVs_Infrastructure_20190809.pdf,* accessed October 8, 2019.

Houston, S. 2019. Electric utility investment in truck and bus charging: A guide for programs to accelerate electrification. Cambridge, MA: Union of Concerned Scientists. Online at *www.ucsusa.org/resources/electric-utility-investment-truck-and-bus-charging,* accessed September 23, 2019.

Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP). 2019. HVIP eligible vehicle catalog. Online at *www.californiahvip.org/how-to-participate/#Eligible-Vehicle-Catalog*, accessed September 23, 2019.

Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP). 2015. HVIP eligible vehicle catalog. Online at *https://web.archive.org/web/20150321055754/http://californiahvip.org/docs/HVIP_Year4_EligibleVehicles.pdf*, accessed September 23, 2019.

ICF. No date a. Comparison of medium- and heavy-duty technologies in California: Technology assessment. San Jose, CA. In press.

ICF. No date b. Comparison of medium- and heavy-duty technologies in California: Scenario analysis. San Jose, CA. In press.

Keegan, M. 2018. Shenzhen's silent revolution: World's first fully electric bus fleet quietens Chinese megacity. *The Guardian,* December 12. Online at *www.theguardian.com/cities/2018/dec/12/silence-shenzhen-world-first-electric-bus-fleet*, accessed October 8, 2019.

Komanduri, A. 2019. Oral presentation, Southern California Association of Governments (SCAG) Modeling Task Force, Los Angeles, CA. January 23. Online at *www.scag.ca.gov/committees/CommitteeDocLibrary/mtf012319_CAVIUS.pdf,* accessed October 8, 2019.

McLane, R., and D. Mullaney. 2019. Shenzen: A city miles ahead. Rocky Mountain Institute, June 30. Online at *https://rmi.org/shenzhen-a-city-miles-ahead*, accessed October 8, 2019.

Nealer, R., D. Reichmuth, and D. Anair. 2015. *Cleaner cars from cradle to grave: How electric cars beat gasoline cars on lifetime global warming emissions.* Cambridge, MA: Union of Concerned Scientists. Online at *www.ucsusa.org/resources/cleaner-cars-cradle-grave,* accessed October 8, 2019.

New York Truck Voucher Incentive Program (NYTVIP). No date. Online at *www.nyserda.ny.gov/All-Programs/Programs/Truck-Voucher-Program*, accessed November 20, 2019.

O'Dea, J. 2019a. More charging infrastructure coming for electric trucks and buses in California. *The Equation*. Cambridge, MA: Union of Concerned Scientists. Blog, August 15. Online at *https://blog.ucsusa.org/jimmy-odea/more-charging-infrastructure-coming-for-electric-trucks-and-buses-in-california*, accessed October 17, 2019.

O'Dea, J. 2019b. Electric airport shuttle buses are taking off. *The Equation*. Cambridge, MA: Union of Concerned Scientists. Blog, June 27. Online at *https://blog.ucsusa.org/jimmy-odea/electric-airport-shuttle-buses*, accessed November 22, 2019.

O'Dea. J. 2018a. Electric vs. diesel vs. natural gas: Which bus is best for the climate? *The Equation*. Cambridge, MA: Union of Concerned Scientists. Blog, July 19. Online at *https://blog.ucsusa.org/jimmy-odea/electric-vs-diesel-vs-natural-gas-which-bus-is-best-for-the-climate*, accessed November 22, 2019.

O'Dea, J. 2018b. California gets one step closer to zero-emission transit buses. *The Equation*. Cambridge, MA: Union of Concerned Scientists. Blog, September 6. Online at *https://blog.ucsusa.org/jimmy-odea/california-gets-one-step-closer-to-zero-emission-transit-buses,* accessed November 22, 2019.

Office of Energy Efficiency & Renewable Energy (EERE). No date. Fact #671: April 18, 2011 average truck speeds. Washington, DC: US Department of Energy. Online at *www.energy.gov/eere/vehicles/fact-671-april-18-2011-average-truck-speeds,* accessed September 23, 2019.

Phadke, A., A. Khandekar, M. McCall, N. Karali, and D. Rajagopal. 2019. Long-haul battery electric trucks are technically feasible and economically compelling. Berkeley, CA: Lawrence Berkeley National Laboratory. Online at *http://eta-publications.lbl.gov/sites/default/files/working_paper_005_battery_electric_trucks_906_0.pdf,* accessed October 8, 2019.

Popel, E.J. 2018. *Breathing easy: A survey of zero emission buses across America*. Pasadena, CA: CALSTART. Online at *https://calstart.org/wp-content/uploads/2018/11/Breathing-Easy-August-2018.pdf,* accessed November 16, 2019.

Proterra. 2019. Catalyst: 40 foot bus performance specifications. Online at *www.proterra.com/wp-content/uploads/2019/06/Proterra-Catalyst-40-ft-Spec-Sheet.pdf,* accessed September 23, 2019.

Raudebaugh, D. 2018. Oral presentation, Zero-Emission Bus Conference, Los Angeles, CA. September 10. Online at *http://zebconference.com/wp-content/uploads/2018/04/Dan_Final.pdf.zip*, accessed October 8, 2019.

Reichmuth, D. 2019a. Air pollution from cars, trucks, and buses in the US: Everyone is exposed, but the burdens are not equally shared. *The Equation*. Cambridge, MA: Union of Concerned Scientists. Blog, October 16. Online at *https://blog.ucsusa.org/dave-reichmuth/air-pollution-from-cars-trucks-and-buses-in-the-u-s-everyone-is-exposed-but-the-burdens-are-not-equally-shared,* accessed October 17, 2019.

Reichmuth, D. 2019b. Inequitable exposure to air pollution from vehicles in California: Who bears the burden? Cambridge, MA: Union of Concerned Scientists. Online at *https://www.ucsusa.org/resources/inequitable-exposure-air-pollution-vehicles-california-2019*, accessed September 23, 2019.

Reichmuth, D. 2018. New data show electric vehicles continue to get cleaner. *The Equation*. Cambridge, MA: Union of Concerned Scientists. Blog, March 8. Online at *https://blog.ucsusa.org/dave-reichmuth/new-data-show-electric-vehicles-continue-to-get-cleaner,* accessed September 23, 2019.

Sacramento Municipal Utility District (SMUD). 2019. West Coast power providers explore EV charging for zero-emission shipping along I-5, connecting routes. Press release. Online at *www.smud.org/en/Corporate/About-us/News-and-Media/2019/2019/West-Coast-Clean-Transit-Corridor-Initiative,* accessed September 23, 2019.

Sandhu, G., H. Frey, S. Bartelt-Hunt, and E. Jones. 2014. In-use measurement of the activity, fuel use, and emissions of front-loader refuse trucks. *Atmospheric Environment* 92:557–565. doi:10.1016/j.atmosenv.2014.04.036.

Silver, F., J. Jackson, and B. Lee. 2019. *Zeroing in on ZEBS*. Sacramento, CA: CALSTART. Online at *https://calstart.org/wp-content/uploads/2019/10/Zeroing_In_on_ZEBs_Final_10182018-10.21.19.pdf,* accessed November 16, 2019.

Tesla. No date. Electric vehicle and solar incentives. Online at *www.tesla.com/support/incentives,* accessed November 20, 2019.

Texas Commission on Environmental Quality (TCEQ). No date. Texas Clean Fleet Program. Online at *www.tceq.texas.gov/airquality/terp/tcf.html,* accessed November 20, 2019.

Union of Concerned Scientists (UCS). 2019. What is ZEV? Online at *www.ucsusa.org/resources/what-zev,* accessed September 23, 2019.

US Census Bureau (USCB). 2004. Vehicle Inventory and Use Survey. Washington, DC. Online at *http://web.archive.org/web/20150405052852/http://www.census.gov/svsd/www/vius/Revised2002MDF.zip,* accessed September 23, 2019.

US Census Bureau (USCB). No date. Community faces: Census 2010 population. Washington, DC. Online at *https://factfinder.census.gov/faces/nav/jsf/pages/community_facts.xhtml,* accessed September 23, 2019.

US Department of Transportation (DOT). No date. Freight facts and figures 2017. Washington, DC. Online at *www.bts.dot.gov/sites/bts.dot.gov/files/docs/FFF_2017.pdf,* accessed September 23, 2019.

Wisland, L. 2018. Turning down the gas in California: The role of natural gas in the state's clean electricity future. Cambridge, MA: Union of Concerned Scientists. Online at *www.ucsusa.org/resources/turning-down-gas-california*, accessed October 8, 2019.

Union of Concerned Scientists

FIND THIS DOCUMENT AND TECHNICAL APPENDIX ONLINE:
www.ucsusa.org/resources/ready-work

The Union of Concerned Scientists puts rigorous, independent science to work to solve our planet's most pressing problems. Joining with people across the country, we combine technical analysis and effective advocacy to create innovative, practical solutions for a healthy, safe, and sustainable future.

NATIONAL HEADQUARTERS
Two Brattle Square
Cambridge, MA 02138-3780
Phone: (617) 547-5552
Fax: (617) 864-9405

WASHINGTON, DC, OFFICE
1825 K St. NW, Suite 800
Washington, DC 20006-1232
Phone: (202) 223-6133
Fax: (202) 223-6162

WEST COAST OFFICE
500 12th St., Suite 340
Oakland, CA 94607-4087
Phone: (510) 843-1872
Fax: (510) 843-3785

MIDWEST OFFICE
One N. LaSalle St., Suite 1904
Chicago, IL 60602-4064
Phone: (312) 578-1750
Fax: (312) 578-1751

WEB: www.ucsusa.org

PRINTED ON RECYCLED PAPER USING VEGETABLE-BASED INKS